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STEEL:

A MANUAL FOR STEEL-USERS.

BY

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INTRODUCTION.

TWENTY-SEVEN years of active practice in the manufacture of steel brought the author in daily contact with questions involving the manipulation of steel, its properties, and the results of any operations to which it was subjected.

Blacksmiths, edge-tool makers, die-makers, machine-builders, and engineers were continually asking questions whose answers involved study and experiment.

During these years the Bessemer and the open-hearth processes were developed from infancy to their present enormous stature; and the shadows of these young giants, ever menacing to the expensive and fragile crucible, kept one in a constant state of watching, anxiety, and more study.

The literature of steel has grown with the art; its books are no longer to be counted on the fingers, they are to be weighed in tons.

Then why write another?

Because there seems to be one little gap. Metallurgists and scientists have worked and are still working; they have given to the world much information for which the world should be thankful.

Engineers have experimented and tested, as they never did before, and thousands of tables and results are re-

corded, providing coming engineers with a mine of invaluable wealth. Steel-workers and temperers have written much that is of great practical value.

Still the questions come, and they are almost always those involving an intimate acquaintance with the properties of steel, which is only to be gained by contact with both manufacturers and users. In this little manual the effort is made to fill this gap and to give to all steel-users a systematic, condensed statement of facts that could not be obtained otherwise, except by travelling through miles of literature, and possibly not then. There are no tables, and no exact data; such would be merely a re-compilation of work already done by abler minds.

It is a record of experiences, and so it may seem to be dogmatic; the author believes its statements to be true—they are true as far as his knowledge goes; others can verify them by trial.

If the statements made prove to be of value to others, then the author will feel that he has done well to record them; if not, there is probably nothing said that is likely to result in any harm.

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STEEL:

A MANUAL FOR STEEL USERS.

I.

GENERAL DESCRIPTION OF STEEL AND OF MODES OF ITS MANUFACTURE.

STEEL may be grouped under four general heads, each receiving its name from the mode of its manufacture; the general properties of the different kinds are the same, modified to some extent by the differences in the operations of making them; these differences are so slight, however, that after having mentioned them the discussion of various qualities and properties in the following pages will be general, and the facts given will apply to all kinds of steel, exceptions being pointed out when they occur.

The first general division of steel is cemented or converted steel, known to the trade as blister-steel, German, shear, and double-shear steel.

This is probably the oldest of all known kinds of steel, as there is no record of the beginning of its manufacture. This steel is based upon the fact that when iron not saturated with carbon is packed in carbon, with all air excluded,

and subjected to a high temperature,—any temperature above a low red heat,—carbon will be absorbed by the iron converting it into steel, the steel being harder or milder, containing more or less carbon, determined by the temperature and the time of contact.

Experience and careful experiment have shown that at a bright orange heat carbon will penetrate iron at the rate of about *one eighth of an inch in twenty-four hours.* This applies to complete saturation, above 100 carbon; liquid steel will absorb carbon with great rapidity, becoming saturated in a few minutes, if enough carbon be added to cause saturation.

MANUFACTURE OF BLISTER-STEEL.

Bars of wrought iron are packed in layers, each bar surrounded by charcoal, and the whole hermetically sealed in a fire-brick vessel luted on top with clay; heat is then applied until the whole is brought up to a bright orange color, and this heat is maintained as evenly as possible until the whole mass of iron is penetrated by carbon; usually bars about three quarters of an inch thick are used, and the heat is required to be maintained for three days, the carbon, entering from both sides, requiring, three days to travel three eighths of an inch to the centre of the bar. If the furnace be running hot, the conversion may be complete in two days, or less. The furnace is then cooled and the bars are removed; they are found to be covered with numerous blisters, giving the steel its name.

The bars of tough wrought iron are found to be converted into highly crystalline, brittle steel. When blister-steel is heated and rolled directly into finished bars, it is known commercially as

GERMAN STEEL.

When blister-steel is heated to a high heat, welded under a hammer, and then finished under a hammer either at the same heat or after a slight re-heating, it is known as

SHEAR-STEEL, OR SINGLE-SHEAR.

When single-shear steel is broken into shorter lengths, piled, heated to a welding heat and hammered, and then hammered to a finish either at that heat or after a slight re-heating, it is known as

DOUBLE-SHEAR STEEL.

Seebohm gives another definition of single-shear, and double-shear; probably both are correct, being different shop designations.

Until within the last century the above steels were the only kinds known in commerce. There was a little steel made in India by a melting process, known as Wootz. It amounted to nothing in the commerce of the world, and is mentioned because it is the oldest of known melting processes.

Although converted steel is so old, and so few years ago was the only available kind of steel in the world, nothing more need be said of it here, as it has been almost superseded by cast steel, superior in quality and cheaper in cost, except in crucible-steel.

Inquiring readers will find in Percy, and many other works, such full and detailed accounts of the manufacture of these steels that it would be a waste of space and time to reprint them here, as they are of no more commercial importance.

In the last century Daniel Huntsman, of England, a maker of clocks, found great difficulty in getting reliable, durable, and uniform springs to run his clocks. It occurred to him that he might produce a better and more uniform article by fusing blister-steel in a crucible. He tried the experiment, and after the usual troubles of a pioneer he succeeded, and produced the article he required. This founded and established the great *Crucible-cast-steel* industry, whose benefits to the arts are almost incalculable; and none of the great inventions of the latter half of this nineteenth century have produced anything equal in quality to the finer grades of crucible-steel.

CRUCIBLE-CAST STEEL

is the second of the four general kinds of steel mentioned in the beginning of this chapter.

Although Huntsman succeeded so well that he is clearly entitled to the credit of having invented the crucible process, he met with many difficulties, from porosity of his ingots mainly; this trouble was corrected largely by Heath by the use of black oxide of manganese. Heath attempted to keep his process secret, but it was stolen from him, and he spent the rest of a troubled life in trying to get some compensation from the pilferers of his process. An interesting and pathetic account of his troubles will be found in Percy.

Heath's invention was not complete, and it was finished by the elder Mushet, who introduced in addition to the oxide of manganese a small quantity of ferro-manganese, an alloy of iron and manganese; and it was now possible, with care and skill, to make a quality of steel which for uni-

formity, strength, and general utility has never been equalled.

Crucible-steel was produced then by charging into a crucible broken blister-steel, a small quantity of oxide of manganese, and of ferro-manganese, or Spiegel-eisen, covering the crucible with a cap, and melting the contents in a coke-furnace, a simple furnace where the crucible was placed on a stand of refractory material, surrounded by coke, and fired until melted thoroughly.

The first crucibles used, and those still used largely in Sheffield, were made of fire-clay; a better, larger, and more durable crucible, used in the United States exclusively, and in Europe to some extent, is made of plumbago, cemented by enough of fire-clay to make it strong and tough. As the demands for steel increased and varied it was found that the carbon could be varied by mixing wrought iron and blister-bar, and so a great variety of tempers was produced, from steel containing not more than 0.10% of carbon up to steel containing 1.50% to 2% of carbon, and even higher in special cases.

It was soon found that the amount of carbon in steel could be determined by examining the fractures of cold ingots; the fracture due to a certain quantity of carbon is so distinct and so unchanging for that quantity that, once known, it cannot be mistaken for any other. The ingot is so sensitive to the quantity of carbon present that differences of .05% may be observed, and in everyday practice the skilled inspector will select fifteen different tempers of ingots in steels ranging from about 50 carbon to 150 carbon, the mean difference in carbon from one temper to another being only .07%. And this is no guess-work;—no chemical color determination will approach it in accuracy,

and such work can only be checked by careful analysis by combustion.

This is the steel-maker's greatest stronghold, as it is possible by this means for a careful, skilful man to furnish to a consumer, year after year, hundreds or thousands of tons of steel, not one piece of which shall vary in carbon more than .05% above or below the mean for that temper.

The word "temper" used here refers to the quantity of carbon contained in the steel, it is the steel-maker's word; the question, What temper is it? answered, No. 3, No. 6, or any other designation, means a fixed, definite quantity of carbon.

When a steel-user hardens a piece of steel, and then lets down the temper by gentle heating, and he is asked, What temper is it? he will answer straw, light brown, brown, pigeon-wing, light blue, or blue, as the case may be, and he means a fixed, definite degree of softening of the hardened steel.

It is an unfortunate multiple meaning of a very common word, yet the uses have become so fixed that it seems to be impossible to change them, although they sometimes cause serious confusion.

The quantity of carbon contained in steel, and indeed of all ingredients, as a rule, is designated in one hundredths of one per cent; thus ten (.10) carbon means ten one hundredths of one per cent; nineteen (.19) carbon means nineteen one hundredths of one per cent; one hundred and thirty-five (1.35) carbon means one hundred and thirty-five one hundredths of one per cent, and so on. So also for contents of silicon, sulphur, phosphorus, manganese and other usual ingredients.

This enumeration will be used in this work, and care

will be taken to use the word "temper" in such a way as not to cause confusion.

It has been stated that crucible-cast steel is made from ten carbon up to two hundred carbon, and that its content of carbon can be determined by the eye, from fifty carbon upwards, by examining the fracture of the ingots. The limitation from fifty carbon upwards is not intended to mean that ingots containing less than fifty carbon have no distinctive structures due to the quantity of carbon; they have such distinctive structures, and the difficulty in observing them is merely physical.

Ingots containing fifty carbon are so tough that they can only be fractured by being nicked with a set deeply, and then broken off; below about fifty carbon the ingots are so tough that it is almost impossible to break open a large enough fracture to enable the inspector to determine accurately the quantity of carbon present; therefore it is usual in these milder steels, when accuracy is required, to resort to quick color analyses to determine the quantity of carbon present. Color analyses below fifty carbon may be fairly accurate, above fifty carbon they are worthless.

As the properties and reliability of crucible-steel became better known the demand increased, and the requirements varied and were met by skilful manufacturers, until, by the year 1860, ingots were produced weighing many tons by pouring the contents of many crucibles into one mould; in this way the more urgent demands were met, but the material was very expensive and the risks in manufacturing were great. About this time, stimulated by the desire of enlightened governments to increase their powers of destruction in war by the use of heavy guns of

greater power than could be obtained by the use of cast iron, and for heavier ship-armor to be used in defence. Mr. Bessemer, of England, now Sir Henry Bessemer, reasoned that if melted cast iron was reduced to wrought iron by puddling, or boiling, by the mere oxidation, or burning out, of the excess of carbon and silicon from the cast iron, that the same cast iron might be reduced to steel in large masses by blowing air through a molten mass in a close vessel, retaining enough heat to keep the mass molten so that the resulting steel could be poured into ingots as large as might be desired. At about the same time, or a little earlier, Mr. Kelly, of the United States, devised and patented the same method. Both of these gentlemen demonstrated the potencies of their invention, and neither brought it to a successful issue.

To persistent and intelligent iron-masters of Sweden must be given the credit of bringing the process of Bessemer to a commercial success, and so they gave to the world pneumatic or Bessemer steel, the latter name holding, properly, as a just tribute to the inventor, and this inaugurated the third general division:

BESSEMER STEEL.

Bessemer steel is made by pouring into a bottle-shaped vessel lined with refractory material a mass of molten cast iron, and then blowing air through the iron until the carbon and silicon are burned out. The gases and flame resulting escape from the mouth of the vessel.

The combustion of carbon and silicon produce a temperature sufficient to keep the mass thoroughly melted, so

that the steel may be poured into moulds making ingots of any desired size.

In the beginning, and for many years, the lining of the vessel was of silicious or acid material, and it was found that all of the phosphorus and sulphur contained in the cast iron remained in the resulting steel, so that it was necessary to have no more of these elements in the cast iron than was allowable in the steel. The higher limit for phosphorus was fixed at ten points (.10%), and that is the recognized limit the world over. When Bessemer pig is quoted, or sold and bought, it means always a cast iron containing not more than ten phosphorus.

In regard to sulphur, it was found that if too much were present the material would be red-short, so that it could not be worked conveniently in the rolls or under the hammer, and that when the amount of sulphur present was not enough to produce red-shortness it was not sufficient to hurt the steel.

As red-short material is costly and troublesome to the manufacturer, it was not found necessary to fix any limit for sulphur, because the makers could be depended upon to keep it within working limits.

Later investigations prove this to be a fallacy, as much as ten or even more sulphur has been found in broken rails and shafts, the steel having made workable by a percentage of manganese. (See the results of Andrews's investigation given in Chap. X.)

During the operation of blowing Bessemer steel the flame issuing from the vessel is indicative of the elimination of the elements, and it is found that while the combustion is partially simultaneous the silicon is all removed before the carbon, and the characteristic white flame

towards the end of the blow is known as the carbon flame; when the carbon is burned out, this flame drops suddenly and the operator knows that the blow is completed. Any subsequent blowing would result in burning iron only. During the blow the steel is charged heavily with oxygen, and if this were left in the steel it would be rotten, red-short, and worthless. This oxygen is removed largely by the addition of a predetermined quantity of ferro-manganese, usually melted previously and then poured into the steel.

The manganese takes up the greater part of the oxygen, leaving the steel free from red shortness and easily worked.

The fact that the phosphorus of the iron remained in the steel notwithstanding the active combustion and high temperature led to the dictum that at high temperatures phosphorus could not be eliminated from iron. This conclusion was credited because in some of the so-called direct processes of making iron where the temperature was never high enough to melt steel all, or nearly all, of the phosphorus was removed from the iron.

For many years steel-makers the world over worked upon this basis, and devoted themselves to procuring for their work iron containing not more than ten (.10) phosphorus, now universally known and quoted as Bessemer iron.

Two young English chemists, Sidney Gilchrist Thomas and Percy C. Gilchrist, being careful thinkers, concluded that the question was one of chemistry and not one of temperature; accordingly they set to work to obtain a basic lining for the vessel and to produce a basic slag from the blow which should retain in it the phosphorus of the

iron. After the usual routine of experiment, and against the doubtings of the experienced, they succeeded, and produced a steel practically free from phosphorus. For the practical working of their process it was found better, or necessary, to use iron low in silicon and high in phosphorus, using the phosphorus as a fuel to produce the high temperature that is necessary instead of the silicon of the acid process. In the acid process it is found necessary to have high silicon—two per cent or more—to produce the temperature necessary to keep the steel liquid; in the Thomas-Gilchrist process phosphorus takes the place of silicon for this purpose.

In this way the basic Bessemer process was worked out and became prominent.

The basic Bessemer process is of great value to England and to the continent of Europe by enabling manufacturers to use their native ores, which are usually too high in phosphorus for the acid process, so that before this invention nearly all of the ores for making Bessemer steel were imported from Sweden, Spain, and Africa.

The basic process has found little development in the United States, because the great abundance of pure ore keeps the acid process the cheaper, except in one or two special localities. Where the basic process is profitable in the United States, it is worked successfully.

At about the time that Bessemer made his invention William Siemens, afterward Sir William, invented the well-known regenerative gas-furnace. A Frenchman named Martin utilized this furnace to melt steel in bulk in the hearth of the furnace, developing what was known for some years as Siemens-Martin steel, or open-hearth steel; the latter name has prevailed, and open-hearth steel is

the fourth of the general kinds of steel mentioned in the beginning of this chapter.

At first open-hearth steel was made upon a specially prepared sand bottom, by first melting a bath of cast iron and then adding wrought iron to the bath until by the additions of wrought iron and the action of the flame the carbon and silicon of the cast iron were reduced until the whole became a mass of molten steel. Sometimes iron ore is used instead of wrought iron as the reducing agent; this is called the pig and ore process. Now in general practice wrought iron, steel scrap, and iron ore are used, sometimes alone and sometimes together, as economy or special requirements make it convenient.

It was found as in the Bessemer, so in the open-hearth, the sulphur and the phosphorus of the charge remained in the steel, making it necessary to see that in the charge there was no more of these elements than the steel would bear.

This is known now as the acid open-hearth process.

After the success of the basic Bessemer process was assured the same principle was tried in the open-hearth; a basic bottom of dolomite or of magnesite was substituted for the acid sand bottom, and care was taken to secure a basic slag in the bath.

Success was greater than in the Bessemer; phosphorus was eliminated and a better article in every way was made by this process, now used extensively over the whole civilized world.

This is the basic open-hearth process.

Neither the basic Bessemer process nor the basic open-hearth removed sulphur, so that this element must still be

kept low in the original charge, until some way shall be found for its sure and economical elimination.

The four general divisions, then, are:

Converted or Cemented Steel.

Crucible-cast Steel.

Bessemer $\left\{\begin{array}{l}\text{Acid}\\ \text{Basic}\end{array}\right\}$ Cast Steel.

Open-hearth $\left\{\begin{array}{l}\text{Acid}\\ \text{Basic}\end{array}\right\}$ Cast Steel.

Little or nothing more will be said of the first kind, as it has been so thoroughly superseded by the cast steels. After a statement of the most patent applications and uses of the different cast steels the discussions which follow will apply to all, because practically they are all governed by the same general laws.

II.

APPLICATIONS AND USES OF THE DIFFERENT KINDS OF STEEL.

Where exact uniformity of composition is not a necessity, and where welding is required, cemented or converted steel may be preferred to cast steel, because the converted bar retains the occluded layers of slag which give to wrought iron its peculiar welding properties, and for this reason blister- or shear-steel may be welded more easily and surely than cast steel. For tires, composite dies, and many compound articles this steel will do very well, and it may be worked with good results by almost any smith of ordinary skill; however, owing to the more uniform structure and the greater durability of the cast steels, they have, even for these purposes, almost entirely displaced the more easily worked, but less durable, cemented steels.

CRUCIBLE-CAST STEEL.

For all purposes crucible-steel has proved to be superior to all others; it is well known to all experienced and observing workers in steel that, given an equal composition, crucible is stronger and more reliable in every way than any of the other kinds of steel.

This may read like a mere dictum, and it might be asked properly, What are the proofs?

The proofs are wanting for two reasons: first, because

crucible-steel is so expensive that except for gun parts, armor, and such uses where expense could be ignored, crucible-steel never came into extensive use for structural purposes; second, that while thousands upon thousands of tests of the cheaper steels are recorded and available to engineers very few of such tests have been made on crucible-steel, simply because it has not been used for structural purposes.

On the other hand, intelligent makers of crucible-steel have for self-preservation made careful study of the relative properties of the different steels in order that they might know what to expect from the cheaper processes. In this way they have surrendered boiler-steel, spring-steel, machinery-steel, battering-tool steel, cheap die-steel, and many smaller applications; not because they could not produce a better article, but because the cheaper steels met the requirements of consumers satisfactorily, and therefore they could not be expected to pay a higher price for an article whose superiority was not a necessity in their requirements.

Still this stated superiority is proven best by the fact that many careful consumers who have special reasons for studying durability as against first cost adhere to the higher priced crucible-steel for such uses as, for instance, parts of mining- and quarrying-drills, high-speed spindles, in cotton-mills, and in expensive lathes and machines of that kind.

This sort of testimony should be more conclusive than that of interested steel-makers, because these men pay their own money for the higher priced material, and because men who are most careful of the quality of their produce and of their reputation are the most clear-headed and most sensible men of their class; they have

the best business and the greatest success. Such men are not fools; they may be depended upon to try everything of promise with the greatest care, and to use only that thing which pays them best. In fact such men do use the cheaper steels freely wherever they can do so safely.

A good car-spring, carriage-spring, or wagon-spring is made from Bessemer or open-hearth steel, a spring that will wear out the car or carriage; it would be stupid then to buy more expensive steel for such purposes, for even if crucible-steel would wear out two cars or two wagons the owner never expects to take the springs out of an old wagon to put them under a new one.

On the other hand, the watch-spring maker or the clock-spring maker will find a great advantage in using the very best crucible-steel that can be made.

A sledge, a maul, or a hammer can be made of such excellent quality from properly selected Bessemer or open-hearth steel that it would be foolish for makers of such tools to continue to buy crucible-steel, even though they knew it to be superior, for lower first cost in such cases outweighs superiority that cannot be shown for a number of years.

Locomotive-boilers, crank-pins, slide-rods, connecting-rods, and springs can be made of such good quality of Bessemer or open-hearth steel that, like the "one-horse shay," the whole machine will wear out at the same time practically, and that a good long time; there would be no reason in this case for using crucible-steel for one or more of these parts, although twenty-five years ago it was by means of crucible-steel that engineers learned to use steel for these purposes.

A good cam for an ordinary machine, such as a shear or

punch, may be made of Bessemer or open-hearth steel where greater strength and endurance are required than can be had in cast iron; on the other hand, makers of cams for delicately adjusted high-speed machines where intricacy and accuracy are necessary will touch nothing but the very best crucible-steel of fine-tool quality for their work. It is of no use to suggest the greater cheapness of the other steels; they have tried them thoroughly, and they know that in their case the highest priced is the cheapest.

This superiority of crucible-steel has been doubted, because the claim appeared to rest solely upon the statements of steel-makers, and not to have any scientific basis; there is, however, a scientific basis for the fact. Given three samples of steel of say the following composition:

	Crucible.	Open-hearth.	Bessemer.
Carbon................	1.00	1.00	1.00
Silicon................	.10	.10	.10
Phosphorus...........	.05	.05	.05
Sulphur...............	.02	.02	.02
Copper, arsenic, etc.....	traces		

Why should there be any difference in the strength of the three? In mere tensile strength in an untempered bar the difference might not be very great, although all experienced persons would expect the crucible to show the highest; but it is not necessary to make the claim, because we have not enough tests of crucible-steel to enable us to establish a mean, and one or two tests are insufficient to establish a rule in any case.

There have been made, however, hundreds of tests of hardened and tempered samples by the most expert persons, with one invariable result: the crucible-steel is in-

comparably finer and stronger than the others, and the open-hearth is almost invariably stronger and finer than the Bessemer.

Unfortunately for the argument these tests cannot be recorded so as to be intelligible to the non-expert, because we cannot tabulate the result of the touch of the expert hand or the observation of the experienced eye.

For a time it was popular to call these differences mysteries, and so let them pass; this, however, was not satisfactory, and the question was studied carefully for the physical reasons which must exist.

Much thought led to the conclusion that the reason lay with the three elements oxygen, nitrogen, and hydrogen; they are known to exist in greater or less quantity in all iron and steel.

It is known that the presence of oxygen beyond certain small limits produces red-shortness and general weakness; it is probably a much more hurtful element than phosphorus or sulphur, but no quantitative method for its determination has been worked out; there is an effort now being made to develop a simple and expeditious oxygen determination, and it is to be hoped that it will be successful.

In the crucible no more oxygen, hydrogen, or nitrogen can get into the steel than is contained in the material charged and in the atmosphere of the crucible, or than may penetrate the walls of the crucible during melting. In the open hearth the process is an oxidizing one, and besides the charge is swept continuously by hot flames containing all of these elements.

In the Bessemer process the conditions are worse still,

as these elements are all blown through the whole mass of the steel.

We know the effect of oxygen and how to eliminate it practically.

Percy gives the effects of nitrogen as causing hardness and extreme brittleness, and giving to iron or steel a brassy lustre. Such a brassy lustre may be seen frequently in open-hearth or Bessemer steel, and occasionally in crucible-steel. When seen in crucible-steel it is known to be due to the fact that the cap of the crucible became displaced, exposing the contents to the direct action of the flame. Of the effect of hydrogen we know less; there is no reason apparent why it may not be as potent as the others.

Ammonia in sufficient quantity to be detected by the nose has often been observed in open-hearth and Bessemer steel.

To settle the nitrogen question Prof. John W. Langley developed some years ago a very delicate and accurate process for the determination of nitrogen even in minute quantities; the process was tedious and expensive, so that it was not adapted for daily use; it involved the careful elimination of nitrogen from all of the reagents to be used, requiring several days' work, in each case to prepare for only a few nitrogen determinations.

By this process it was found, in every one of many trials, that crucible-steel contained the least amount of nitrogen, open-hearth steel the next greater quantity, and Bessemer steel the greatest amount. He found no exceptions to this. For many years great efforts had been made both in Europe and in the United States to make by the Bessemer or the open-hearth process a cheap melting-product to

be used in the crucible instead of the expensive irons which so far have proved to be necessary to give the best results.

There appeared to be no difficulty in making a material as pure chemically, or purer, than the most famous irons in the world, and this material was urged upon the crucible-steel makers. Careful tests of such material failed to produce the required article; in fact it was demonstrated over and over again that an inferior wrought iron would produce a stronger steel than this very pure steel melting-material, and crucible-steel makers were compelled to adhere to the more costly irons to produce their finer grades.

Prof. Langley determined the nitrogen in a given quantity of open-hearth and Bessemer steel; this same material was then melted in a crucible, and it was found that the resulting ingots contained nearly as much nitrogen as the original charge. The quantity was reduced slightly; still this steel contained more nitrogen than any other sample of crucible-steel that he had tested. The physical test of this trial steel showed the usual weakness of the Bessemer or open-hearth steel, as compared to crucible-steel.

The next step was to try to get rid of nitrogen by the use of some affinity, as oxygen is removed by manganese. Boron and titanium seemed to be the most feasible elements; boron appeared to offer less chance of success, and titanium was selected. A ferro-titanium containing six per cent of titanium was imported from Europe at some expense. As the most careful and exacting analyses of this material failed to reveal a trace of titanium, it was not used.

After many futile efforts Langley succeeded, by means of

electric heat, in reducing rutile and producing a small quantity of an alloy of iron and titanium. A trial of this alloy, although not conclusive, led to the belief that such an alloy could be used successfully to eliminate nitrogen; but as its cost, about two dollars a pound, was prohibitory of any commercial use, the subject was not pursued farther.

Although we know these elements only as gases, there is no reason to suppose that their atoms may not be as potent, when added to steel, as atoms of carbon, silicon, phosphorus, or any other substance.

Such are the facts for crucible-steel as far as they are known; it is vastly more expensive than any other kind of steel, yet for the present it holds its own unique and valuable place in the arts.

For all tools requiring a fine edge for cutting purposes, such as lathe-tools, drills, taps, reamers, milling cutters, axes, razors, pocket-knives, needles, graving-tools, etc.; for fine dies where sharp outline and great endurance are required; for fine springs and fine machinery parts and fine files and saws, and for a hundred similar uses, crucible-cast steel still stands pre-eminent, and must remain so until some genius shall remove from the cheaper steels the elements that unfit them for these purposes.

As stated before, crucible-steel is divided into fifteen or more different tempers, ranging in carbon from .50 to 1.50. Each of these tempers has its specific uses, and a few will be pointed out in a general way.

.50 to .60 carbon is best adapted for hot work and for battering-tools.

.60 to .70 carbon for hot work, battering-tools, and tools of dull edge.

.70 to .80 carbon for battering-tools, cold-sets, and some forms of reamers and taps.

.80 to .90 carbon for cold-sets, hand-chisels, drills, taps, reamers, and dies.

.90 to 1.00 carbon for chisels, drills, dies, axes, knives, and many similar purposes.

1.00 to 1.10 carbon for axes, hatchets, knives, large lathe-tools, and many kinds of dies and drills if care be used in tempering them.

1.10 to 1.50 carbon for lathe-tools, graving-tools, scribers, scrapers, little drills, and many similar purposes.

The best all-around tool-steel is found between .90 and 1.10 carbon; steel that can be adapted safely and successfully to more uses than any other temper.

At somewhere from .90 to 1.00 carbon, iron appears to be saturated with carbon, giving the highest efficiency in tools and the highest results in the testing-machine except for compressive strains. More will be said upon this point in treating of the carbon-line.

Much more could be said about the uses for the different tempers of steel; it would be easy to write out in great detail the exact carbon which experience has shown to be best adapted to any one of hundreds of different uses, but it would only be confusing and misleading to a great many people.

It is within the experience of every steel-maker that men are just as variable as steel, and the successful steel-maker must familiarize himself with the personal equations of his patrons. One man on the sunny side of a street may be making an excellent kind of tool from a certain grade and temper of steel, and be perfectly happy and prosperous in its use. His competitor on the shady side of the street

may fail in trying to use the same steel for the same purpose and condemn it utterly.

The know it all agent will condemn the latter man with an intimation that his ears are too long, and so lose his trade. The tactful agent will supply him with steel a temper higher or a temper lower, until he hits upon the right one, and so will retain both men on his list; and both men will turn out equally good products.

Few men know their own personal equations, and the best way for a steel-user to do is to tell the steel-maker what he wants to accomplish, and put upon him the responsibility of selecting the best temper.

It costs no more to make and to provide one temper than another; therefore the one inducement of the steel-maker is to give his patron that which is best adapted to his use. This plan puts all of the responsibility upon the steel-maker, just where it ought to be, because he should know more about the adaptability of his steel than any other person.

BESSEMER STEEL.

Bessemer steel is probably the cheapest of all grades of steel; that is to say, it can be made so rapidly, so continuously, and in such enormous quantities that a greater output per dollar invested can be made than by either of the other processes. Again, the work is controlled and operated by machinery to a much greater extent than in the other processes; therefore the cost of labor per ton of product both for skilled and unskilled labor is less than in the crucible or the open-hearth method.

This being the case, it might be inferred that the result would be the eventual driving out of all other steels by this, the cheapest. This would be the inevitable result

if Bessemer steel were as well adapted to all purposes as either of the other kinds of steel; there are limitations which prevent this.

The source of heat in the Bessemer process is in the combustion of the elements of the charge, there is no extraneous source of heat; therefore, if the heat be too cold, there is no way to remedy it unless it be by the addition of ferro-silicon and more blowing; if it be too hot, it may be allowed to stand a few minutes to cool. Still in either case the remedy is somewhat doubtful. This limitation must not be taken as being fatal to good work, for in skilful hands such cases are rare, and the product is generally fully up to the standard of good work.

As there is no known sure way of stopping the blow at a given point in the operation to produce a steel of required carbon, it is usual to blow clear down, that is, to burn out all of the carbon practically and then to re-carbonize by the addition of spiegel-eisen or ferro-manganese. It is necessary, also, to add the manganese in one of these forms to remove the oxygen introduced during the blow; this must be done quickly, and all accomplished before the metal becomes too cold for pouring into ingots.

So little time for reactions is available that it is doubtful if the material is ever quite as homogeneous as it can be made by either of the other processes.

Notwithstanding these limitations, which are not mentioned to throw doubt upon the process, but merely to inform readers fully so as to enable them to judge rightly as to what may be expected, enormous quantities of good, reliable Bessemer steel are made to meet many requirements.

For good, serviceable, cheap rails Bessemer steel stands

pre-eminent, and if it found no other use it would be difficult to overestimate the benefit to the world of this one great success.

Bessemer steel is used largely for a great number of purposes, Bessemer billets being now as regular an article of commerce as pig iron.

For wire for all ordinary purposes; for skelp to be worked into butt-welded and lap-welded tubing; for wire nails, shafting, machinery-steel, tank-plates, and for many other uses, Bessemer steel has absorbed the markets almost entirely.

For common cutlery, files, shovels, picks, battering-tools, and many such uses it contests the market with open-hearth steel; and while many engineers now specify that their structural shapes, plates, beams, angles, etc., must be of open-hearth steel, there are many eminent engineers who see no need for this discrimination, they being satisfied that if their requirements are met the process by which they are met is a matter of indifference.

OPEN-HEARTH STEEL.

As in the Bessemer process, so in the open-hearth, carbon and silicon are burned out, phosphorus is removed on the basic hearth, and the sulphur of the charge remains in the steel. During the operation oxygen and nitrogen are absorbed by the steel, although not quite so largely as in the Bessemer process, so that practically the chemical limitations are the same in each.

The open-hearth reductions are much slower than in the Bessemer, each heat requiring from five to eight hours for its completion; the furnace must be operated by a skilled man of good judgment, so that more time and more skilled

labor per ton of product are required than in the Bessemer, and the making of an equal quality as cheaply in the open-hearth is problematical. The open-hearth has extraneous sources of heat at the command and under the control of the operator, and there need be no cold heats, and no too hot heats.

The time for reactions is much longer, and for this reason they ought to be more complete, and they are so in good hands; yet it is a fact that, as the operation is a quiet one compared to the Bessemer, and not nearly so powerful and energetic, a careless or unskilful operator may produce in the open hearth an uneven result that is quite as bad as anything that can be brought out of a Bessemer converter. The process that eliminates the human factor has not yet been invented.

For fine boiler-plates, armor-plates, and gun parts open-hearth steel has won its place as completely as has the crucible for fine-tool steel or the Bessemer for rails.

For all intermediate products there is a continued race and keen competition, so that it is impossible to draw any hard and fast line between the products of the three processes where they approach each other; the only clear distinctions are at the other extremes.

Owing to the power to hold and manipulate a heat in the open-hearth it is safe to say that it is superior to the Bessemer in the manufacture of steel castings; and owing to its much greater cheapness it is difficult for the crucible to compete with it at all in this branch of manufacture.

In conclusion of this chapter it is safe to say that in good hands these processes are all good, and each has its own special function to perform.

III.

ALLOY STEELS AND THEIR USES.

In addition to the four general kinds of steel treated of in the last chapter there are a number of steels in the market which contain other metals, and which may be termed properly alloy steels, to distinguish them from carbon steel, or the regular steels of world-wide use which depend upon the quantity of carbon present for their properties. The most generally known of the alloy steels is the so-called Self-Hardening steel.

Self-hardening steel is so called because when it is heated to the right temperature,—about a medium orange color,—and is then allowed to cool in the air, it becomes very hard. This steel is so easily strained that it is impossible, as a rule, to quench it in water without cracking it. It may be quenched in a blast of air without cracking, and so be made much harder than if it be allowed to cool more slowly in a quiet atmosphere. If it be quenched in oil or water, it will become excessively hard, much harder than when quenched in air, and it will almost invariably be cracked, or if it be not cracked it will be so excessively brittle as to be of little use.

Self-hardened steel is so hard in what may be called its natural condition. that is, in ordinary bars, that it cannot be machined, drilled, planed, or turned in a lathe.

By keeping it in an annealing-furnace at about bright

orange heat for about twenty-four to thirty-six hours, and then covering it with hot sand or ashes in the furnace, and allowing about the same time for it to cool, it may be annealed pretty thoroughly so that it may be machined readily.

When annealed in this way and formed into cutters of irregular shape, or dies, it has been found so far not to be economical or well adapted to such work, so that up to the present time annealing is more of a scientific than a useful fact.

Self-hardened steel has the useful property of retaining its hardness when heated almost to redness; therefore it may be used as a lathe or similar cutter upon hard work, such as cutting cast iron and other metals, at a much higher speed than is possible with ordinary steel, which would be softened by the heat generated by the high speed. This property makes self-hardened steel very useful and economical for many purposes.

Self-hardened steel is an alloy of iron, carbon, tungsten, and manganese, and some brands contain chromium in addition to these, and it is claimed, and probably truly, that the chromium improves the quality of the steel.

It was supposed for a long time that tungsten was the hardener that gave to self-hardened steel its peculiar properties. By means of an open hearth, steel was produced containing about 3% tungsten and little carbon and manganese. This steel worked like any mild steel, except that it was hot-short and difficult to forge. It was not hard and had no hardening properties; that is, it did not harden in the ordinary sense when quenched in water. The addition of carbon to this steel, keeping the manganese low, produced a steel very difficult to work, which would harden

like ordinary steel when quenched, and which had no self-hardening properties whatever. The addition of $2\frac{1}{2}\%$ to 3% of manganese to this steel produced self-hardening steel having the usual properties.

Manganese, then, is the metal that gives the self-hardening property, and this might have been anticipated by considering the properties of Hadfield's manganese steel, which, when it contains above 7% manganese, cannot be annealed so that it can be machined or drawn into wire. From this it might be inferred that tungsten is not a necessary constituent of self-hardened steel; that it performs an important function will be shown presently. Tests of the iron-tungsten alloy low in carbon gave only a small increase in strength above ordinary low cast steel containing little carbon; it was difficult and troublesome to work, and more expensive than the common steels, so that its production presented no advantages. When carbonized, it was fine-grained and could be made exceedingly hard; it was brittle, and compared to very ordinary cast steel comparatively worthless.

In self-hardened steel tungsten is the mordant that holds the carbon in solution and enables the steel to retain its hardness at comparatively high temperatures. That it does hold the carbon in solution may be proved in a moment by a beautiful test, first observed by Prof. John W. Langley.

When a piece of carbon steel is pressed against a rapidly running emery wheel, there is given off a shower of brilliant sparks which flash out in innumerable white, tiny stars of great beauty; it is accepted that this brilliancy is due to the explosive combustion of particles of carbon.

When a steel containing as much as three per cent of

tungsten is pressed against the wheel, the entire absence of these brilliant flashes is at once noticeable, and if there be an occasional little flash it only serves to emphasize the absence of the myriads.

Instead there is an emission of a comparatively small number of dull particles, and there is clinging to the wheel closely a heavy band of a deep, rich red color. This red streak is distinctive of the presence of tungsten.

By testing various pieces it was soon observed that different quantities of tungsten gave different sizes of red streaks; as tungsten decreased the width of the band diminished and the number and brilliancy of carbon sparks increased. As little as .10 tungsten will show a fine red line amidst a brilliant display of sparks, and it soon became possible to determine so closely by the streak the quantity of tungsten present that the ordinary analyses for tungsten became unnecessary, except in occasional important cases where analysis was used merely to confirm the testimony of the wheel.

Self-hardening steel, then, is a steel which, owing to the presence of manganese and tungsten, hardens when quenched in quiet air, and which retains its hardness almost up to a red heat.

It may be forged between the temperatures from orange to bright orange; it cannot be worked safely outside of this range. The more quickly it is quenched the harder it will be; and it may be annealed so that it can be machined readily. Therefore it is not self-hardening; it simply has all of the properties of carbon steel modified profoundly by tungsten and manganese. If a piece of this steel will not harden sufficiently by cooling in the air quietly, that difficulty may be remedied by cooling it in

an air-blast; if quenching in an air-blast will not give sufficient hardness, the steel had better be rejected, for quenching in oil or water means almost certain destruction.

As stated before, the range of temperature in which self-hardened steel can be forged safely is much smaller than for a high-carbon steel; it is harder at this heat than carbon steel and not so plastic, so that it requires more care and more heats in working it to tool-shapes.

This steel is so sensitive that it often occurs in redressing it that it will crumble at a heat that was all right in the first working. This difficulty may be remedied by first cutting off the shattered part with a sharp tool,—it must be cut hot,—then heating the piece up to nearly a lemon color, heating it through without soaking it in the fire, and then allowing it to cool slowly in a warm, dry place. After this treatment the steel may be heated and worked as at first. This treatment does not anneal the steel soft, because the heat is not continued long enough, and the cooling is not sufficiently slow; it does relieve the strains in the steel, so that it is plastic and malleable.

This treatment is good in any high steel which has become refractory from previous working.

Self-hardened steel is not as strong in the hardened condition as good high-carbon steel; it has not been used successfully for cutting chilled cast iron, for instance. If made hard enough to cut a chill, it is so brittle that the cutting-edge will crumble instead of cutting; if the temper be let down enough to stop the crumbling, the steel will be softer than the chill, and the edge will curl up instead of cutting.

Owing to the retention of hardness at a higher temperature than carbon steel will bear this steel is capable of

doing a great amount of work at high speed, so that for much lathe-work it is cheap at almost any price.

Owing to its brittle, friable nature its use is limited to the simpler forms of tools, and to a narrower range of work than is possible with carbon steel.

CHROME STEEL.

An alloy of chromium with carbon steel has been before the public for many years, and greater claims have been made for it than experience seems to justify. Chrome teel is fine-grained and very hard in the hardened state, and it will do a large amount of work at the first dressing: upon redressing it deteriorates much more rapidly than carbon steel and becomes inferior; it is believed that this is due to a rapid oxidation of the chromium.

It is claimed for it that it will endure much higher heats without injury than carbon steels of the same temper. Intending purchasers will do well to satisfy themselves upon these points before investing too heavily.

SILICON STEEL.

Steel containing two to three per cent of silicon was put upon the markets, and great claims were made for it.

It is exceedingly fine-grained and hardens very hard; it is brittle, much more liable to crack in hardening than ordinary steel, and it is not nearly so strong as carbon steel.

It is made cheaply enough as far as melting goes, but it may not be melted dead, and therefore sound, because long-continued high heat will destroy it; therefore the ingots are more honeycombed than well-melted carbon-steel ingots. The steel will not bear what is known as a welding-heat in steel-working; it is hot-short; for this reason the

bars are more seamy than is usual in carbon steel. Added to this the hot-shortness makes it so difficult to work that the labor cost is high. Altogether, then, silicon steel is expensive, and it presents no extra good qualities in compensation.

MANGANESE STEEL.

The glassy hardness, brittleness, and friability of ferro-manganese and of spiegel-eisen are well known; these are products of the blast-furnace, and the manganese ranges all the way from say 10% up to 80%.

Steel containing from 1% to 3% of manganese is about as brittle and almost as unworkable as spiegel-eisen, and a fair deduction would be that manganese above very small limits will not form any useful alloy with iron. Many a general law of nature has been based upon much more meagre data and has been announced with a great flourish of trumpets: such discoveries are usually heard of no more after the first blare has died away.

R. A. Hadfield, of Sheffield, England, is an inquirer who wants to know, and who is willing to travel the whole road in order to find out. Hadfield discovered that an alloy of iron and manganese containing from 7% to 20% of manganese was a compound possessing many remarkable properties. This alloy is now known as manganese steel.

Manganese steel is both hard and tough to a degree not found in any other metal or alloy.

It is so hard and strong that it cannot be machined with the best of tools made of the finest steel. Castings made of it may be battered into all sorts of shapes as completely as if they were made of the mildest dead-soft steel; still they are too hard to be machined.

The ordinary hardening process toughens this steel instead of hardening it to brittleness.

This steel is non-magnetic, and this property alone would give it exceedingly great value if the steel could only be worked into the required shapes.

Up to this time all attempts to anneal this steel have failed, and this persistent hardness is the best proof that manganese is the real hardener in self-hardened steel. So far carbon and manganese have not been separated in this steel or in any other. Persistent attempts have been made to produce manganese steel low in carbon, but all have been failures, because any operation that burned out the carbon took the manganese with it. The hope was that a non-magnetic alloy might be produced that would be soft enough to work. This may yet be accomplished, and if it should be another great step in the arts will have been taken.

Hard, tough, strong, non-magnetic—what great things may not come out of this when it has been worked out finally?

Since this was written carbonless manganese has been produced which is claimed to contain 98% + of manganese and no carbon, but at present it is sold at $1 per pound. If it can be produced more cheaply, it may lead to a workable non-magnetic alloy of iron and manganese which may prove to be of great value to electricians and to watchmakers.

The uses of manganese steel are large and growing, and it must be regarded as having an established and a prominent place.

It has been stated that in self-hardened steel and in manganese steel manganese is the hardener; it should be

borne in mind that carbon is always present, that it is the one great hardener, but its hardening property in the absence of manganese depends directly upon rapidity of cooling. By rapid cooling steel containing carbon is made harder than glass, and by slow cooling it may be made softer and more ductile than ordinary wrought iron.

Self-hardened steel may be annealed so that it can be machined, but it is by no means as soft and ductile as well-annealed carbon steel. Manganese steel has not been annealed at all; it cannot be annealed by any of the well-known annealing processes; some new way of doing it must be discovered. Therefore it is proper to say that the peculiar hardening properties of these two steels are due to manganese.

NICKEL STEEL.

The addition of a few per cent of nickel to mild steel adds greatly to its strength—so much so that nickel steel is now world-renowned as used in armor-plate for navy vessels, and for great guns. Recent reports from the ordnance bureaus indicate that it will also be of great use in the barrels of small arms, by means of which they may be made lighter, and still of sufficient strength. Nickel is so expensive and it adds so much to the cost of steel that its use for ordinary structural purposes, bridges, etc., has not been found to be economical.

Some years ago careful experiments were made with nickel alloy in a fine grade of high-carbon tool-steel to find out whether such steel would be improved as much as are the mild steels.

In such case the expense would not count, for if the

best steel can be made better there are many users who would gladly pay a higher price for a better service.

The results were not encouraging. The high-carbon nickel steel was not as strong as the same quality of steel without nickel; the mixture seemed to be imperfect, containing little dark specks, supposed to be carbon thrown into the graphitic state. The steel did not refine as well and was not as strong as the carbon steel.

All of this applies to high-carbon tool-steel, hardened and tempered; no tests were made of the steel unhardened, for they would have been of no practical use.

ALUMINUM STEEL.

When a heat of steel is boiling violently, is wild, and unfit to be poured, the addition of a minute quantity of aluminum will have the effect of quieting it quickly. Half an ounce to an ounce of aluminum to a ton of steel will be enough usually, and for this purpose aluminum has become useful to steel-makers. If a little too much aluminum be added, the ingots will pipe from end to end; therefore the use of aluminum is restricted to small quantities. Experiments have shown that a considerable percentage of aluminum adds no good properties to steel; therefore aluminum steel so called may be treated later under a different heading.

IV.

CARBON.

Of all of the abundant elements of nature carbon is presented in the greatest variety of forms, and admits of the greatest number of useful applications.

In the form of the diamond it is the hardest of substances, and is the base used in determining the comparative hardness of all others.

In the form of graphite it is soft and smooth, and is one of the best and most durable of lubricants.

In the form of soot it is probably the softest of solids.

In the form of coal it is the one great and abundant fuel of the world, while as graphite again it is one of the best of refractory materials.

Hard, soft, highly combustible, almost infusible, refractory, it lends itself to the greatest variety of useful applications. To the iron- and steel-maker or worker it is simply indispensable; as charcoal or coke it is the fuel of the smelter; as gas, either carbon monoxide or as a hydrocarbon, it is the cheapest and most manageable fuel for melting and for all operations requiring heat.

As graphite, plumbago, mixed with a little fire-clay as a binder, it is the best material for crucibles in which to melt metals; as soot it forms the best coating for moulds into which metals are to be cast.

Durable beyond almost any other substance, it would

make the very best paint for metal structures if there were any known way to make it adhere.

CARBON IN IRON.

Carbon may be introduced into iron in any quantity from a few hundredths of one per cent as usually found in wrought iron, and in what is known as dead-soft steel, up to about four per cent as found in cast iron. By the addition of manganese as high as six or seven per cent of carbon has been introduced into iron. Carbon does not form a true alloy with iron, neither does it form any stable chemical compound. Its condition in iron seems to be as variable as it is in nature, and sometimes it has been supposed to be as capricious as it is variable. It is hoped that the reader of these pages will find that there is no caprice about it, that its action is governed by as sure laws as any in nature, and that certain results may be predicated upon any treatment to which it is subjected.

The theories of its actions are as numerous and variable as are the actions themselves, and they will be treated in a separate chapter, this chapter being confined to a statement of known facts.

As stated in Chap. I, carbon may be introduced into iron by heating carbon and iron in contact when air is excluded; and, conversely, carbon is burned out of cast iron by the Bessemer and open-hearth processes to reduce the cast iron to cast steel.

In the crucible any quantity of carbon may be obtained in steel by melting a mixture of high blister-steel and wrought iron, or cast iron and wrought iron, or by charging with wrought iron the necessary quantity of coke or

charcoal. When using plumbago crucibles, the iron takes up some carbon from the crucible; also the spiegel-eisen or ferro-manganese used adds some carbon; and for these two sources of carbon the melter allows when he decides upon the quantity of charcoal needed.

Results from crucible-melting are not strictly uniform; even if every charge were weighed in a chemical balance accurately the product would not be uniform, because one crucible gives off more carbon than another; in one crucible a little more charcoal may be burned and escape as gas than in another; and most variable of all, unless the charcoal has been dried thoroughly, is the quantity of moisture in the charcoal. One charge of charcoal may be dry, and the next may contain as much as twenty-five per cent of moisture; obviously equal weights in such a case would not give equal quantities of carbon to the steel.

In crucible-steel this is no disadvantage; a skilful mixer will get from 75% to 90% of his ingots of the desired temper; the other ingots will all be in demand for other uses, and as he can separate them all with absolute certainty by ocular inspection, as described before, he labors under no fear of bad results.

In the Bessemer process it is usual to burn out all of the carbon and then to add the required amount in the spiegel; for structural steels and for rails this method is satisfactory. For high steel—from fifty to a hundred or more carbon—the spiegel method does not answer so well, because it increases the quantity of manganese to too great an amount; higher carbon is then sometimes put in by the addition of a given quantity of pure pig iron previously melted, or by putting coke in the ladle, but this is very uncertain on account of the tendency of the coke to

float, and be dissipated as a gas instead of entering the steel.

The Darby method is to place in the way of the stream of steel as it is poured from the vessel to the ladle a refractory-lined, funnel-shaped vessel filled with finely divided, but not powdered, coke. As the stream rushes through the coke it absorbs carbon with great rapidity, and it is asserted that the currents and eddies formed in the ladle by the rush of the stream cause an even distribution of carbon. That carbon will be taken up in this way is certain; that a required amount, evenly distributed, can be obtained is not so certain.

In the acid open-hearth as in the Bessemer process for milder steels it is usual to burn the carbon out almost entirely, and then to add the desired amount with the spiegel. Higher carbon may be obtained by the addition of pure pig iron, or by using carbon bricks pasted together with tar and weighted with iron turnings; these bricks may be pushed under the surface in different parts of the bath, and in this way the carbon can be distributed pretty evenly. In good practice now the melt is stopped at the carbon desired with great success, thus saving time and expense. In the basic open-hearth the melter, by the use of a little care and good judgment, stops his melt at the required carbon, and so avoids any additional operations, unless his charge is excessively high in phosphorus and his steel is to be very low in the same; in that case he may have to melt clear down and re-carbonize.

Steel of 130 carbon with phosphorus $<.05$ may be made on the basic hearth from a charge containing 10 to 12 phosphorus without melting below 130 carbon.

If high-carbon Bessemer steel is not uniform, it is not to

be wondered at, but as a matter of fact it is usually found to be fairly uniform, sufficiently so to work well.

If open-hearth steel of high carbon is not uniform, it is clearly because the maker would not take a little trouble to have it so.

Assuming that for convenience cast steel is graded for carbon content by even tens, and that the different tempers are separated half-way between the tens, we have:

Carbon.

.10	including	from	.05	to	.15
.20	“	“	.16	“	.25
.30	“	“	.26	“	.35
.40	“	“	.36	“	.45
.50	“	“	.46	“	.55
.60	“	“	.56	“	.65
.70	“	“	.66	“	.75
.80	“	“	.76	“	.85
.90	“	“	.86	“	.95
1.00	“	“	.96	“	1.05
1.10	“	“	1.06	“	1.15
1.20	“	“	1.16	“	1.25
1.30	“	“	1.26	“	1.35
1.40	“	“	1.36	“	1.45
1.50	“	“	1.46	“	1.55

his covers the usual commercial range from what is known as dead-soft steel up to a high, lathe-temper steel.

Higher steels are used sometimes, even up to 225 carbon, but they are so exceptional that it is not worth while to continue the list above 150.

This list allows a variation of .05 carbon above and below

the datum of each temper; some margin must be had of course, and this is sufficient in the hands of a careful steel-maker; it is found in practice to be satisfactory to the user. Even in the highest lathe-steel where the strains from hardening are the greatest, because the change in volume due to a degree of temperature is the greatest, a variation of three or four points above and below the mean does not make enough difference in the results to throw a skilful temperer off from his desired conditions.

On the other hand, a difference of a full temper will throw the most skilful worker off from the track, and so that much variation is not allowable. For instance, if a man be working 130 carbon, and he should receive a lot of steel of 120 carbon, he would get his work too soft in following his regular methods; then if he doubted himself, as he would be apt to do, and raised his heat to correct his supposed aberration, he would get his work too hard, coarse-grained, and brittle; if he tried to correct this by drawing to a lower temper color, his tools would be too soft. Again, if he received a lot of steel of 140 carbon and proceeded in his regular way, he would get a lot of cracked tools. So that in either case the result would be confusion. It is probable that in almost any case either 120 or 140 carbon would make a thoroughly good tool if the temperer knew what he was working with and adapted his heats to the carbon. But he does not know of the variation, and even if he did he would say, very rightly, that he did not propose to make daily changes in his methods to suit the convenience or the carelessness of the steel-maker.

It must not be understood, however, that this narrow range for each temper limits the capacity of the steel; it merely gives the limit for regular easy working.

To illustrate: A good lathe-tool may be made of 100-carbon steel, and of 150 carbon; but no worker could use these tempers indiscriminately, nor even alternately, although he knew which was which, because he could not change all of his heats say every five minutes and turn out satisfactory work. A spring of given size, and to carry a given load, may be made equally good of 60-carbon steel or of 140 carbon, and such work is done frequently in shops that are attached to steel-works; but the spring-maker must be told beforehand what he is to work with, and he must be given enough of one kind of steel to make say a day's work, so that he can go along regularly. The springs will be good, but the one containing 140 carbon will have the highest elasticity and the most life, although both will have the same modulus of elasticity. The spring-maker who buys his steel will not submit to any such variations, and he ought not to be asked to do it, because one temper of steel costs no more than another, and the selecting out and separating the tempers is only a matter of a little care.

Is it practicable to keep steel uniform in carbon within such narrow limits?

In crucible-steel practice it is very easy to do so. All ingots of 60 carbon upwards up to four or four and one half inches square may be broken completely off at the top, and then the clean fracture will indicate the quantity of carbon invariably, and after the ingot has been glanced at and marked properly it is as easy to put it on its proper pile as to put it on any other. In a good light a competent inspector will mark thirty or forty ingots per minute and do it correctly; it is as easy to the trained eye as it is to read a printed page.

This inspection is so important that it should never be neglected. It is not costly, much less than a dollar a ton.

With larger ingots only a piece can be broken off from the edge, but if the topper does his work properly, enough can be taken off to show the temper clearly. Large ingots containing the contents of a number of crucibles are liable to unevenness of temper from having uneven mixtures in the pots'and from bad teeming into the moulds; this can be detected usually in the ingot inspection, and if not it can be found later during another inspection. Such variations are often called segregations. This question of segregation will be discussed in a future chapter.

In the Bessemer and the open-hearth practice ocular inspection of ingots to determine carbon is not used.

Enough examinations have been made to show that the fractures, although differing from those of crucible-steel, are quite as characteristic, and ocular inspection could be used. The ingots are large usually and to handle and top them would be expensive; but the heats are also large,—from five tons up to thirty tons in one heat,—and as they are supposed to be homogeneous, one chemical carbon analysis is enough for each heat.

Below 50 carbon a quick color analysis is accurate enough; above 50 carbon combustion should be used, for in high carbons the color test in the best hands is only the wildest guess-work.

The ten-point range of carbon is far more difficult to attain in high-carbon open-hearth practice than in the crucible. In one case where the limit fixed in a specification was 90 to 110 carbon, two full tempers, one of the most skilful and successful concerns in the world failed to

meet the specification in twenty-ton and thirty-ton furnaces.

It was supposed at first that the trouble came from using different heats, and large lots of billets were sent out with the heat number stamped on each billet. The same variations were found in every heat, the carbon ranging from 80 to 120. The specification was met without any trouble in five-ton furnace.

This illustration should not lead to the conclusion that practically uniform steel cannot be obtained; there is little doubt that if the 30-ton heats had been stirred thoroughly in the furnace the required limits would have been obtained.

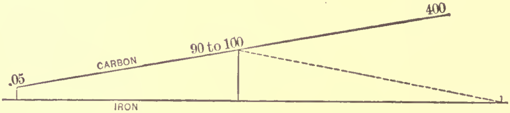
Neither is it to be understood that the same variation would occur in mild steel under 30 carbon. A call for 20 carbon would not result in steel ranging from below 10 to above 30,—such a result would show gross carelessness on the part of the melter,—the variation would go by percentage; thus the variation in the high steel is from 15% below to 15% above the mean of 100, or even as much as 20%.

If 20-carbon steel be required, a variation of 20% would give a range from 16 to 24 carbon, or well within the limits of one temper.

This matter will be considered farther under the head of Segregation.

The appropriate applications of the different tempers of steel have been stated in a general way, with the advice that for all tool purposes it is better to leave the selection of the temper to the steel-maker; also in structural work it may prove to be better to leave the question of temper, or carbon content, to the steel-maker, who should know

how to meet any specification that is within the capacity of steel. On the other hand, every engineer should know what is attainable, and an effort to give this information in more definite form will be made in later chapters. A general view will now be taken of what may be called the carbon-line.



Let the horizontal line represent iron, the inclined line iron plus carbon, and the verticals physical properties.

We do not know the physical properties of pure iron. Assuming them to be uniform, let the vertical at .05 represent the tensile, torsional, transverse, or compressional strength of steel of 5 carbon; then for every increment of carbon up to 90 to 100 there will be an increase of strength to resist any of these strains, increasing in such regular amounts as to make the resulting carbon-line practically straight, as shown in the sketch. Above 100 carbon these resistances will all decrease, except resistance to compression.

So far as it is known, compressive strength increases slightly with the carbon, until cast iron is fairly reached; then the presence of silicon, and the fact that we are dealing with a casting instead of forged or rolled metal, causes a rapid fall in all resistances until the strength is below that of 5-carbon steel.

With increase of carbon there is a reduction of ductility, so that the extension of length and reduction of area

decrease as the strength increases. In every case the engineer must decide how little ductility he can do with safely in securing the ultimate strength or the elastic limit he may require.

The highest strength and the greatest ductility cannot be had together; they are inverse functions one of the other.

If the exact resistances due to carbon were known along the whole line, it would be of great value to give them here but nearly all of the thousands of tests published are influenced by the quantities of silicon, phosphorus, sulphur, manganese, or oxides present, and an effort to determine the effects of the carbon-line exactly would be hazardous.

Kirkaldy's tests of Fagersta steel, published in 1876, furnish a valuable guide in this direction.

Webster's experiments on the effects of the different elements, phosphorus, manganese, etc., are interesting and valuable, but he has not yet tested a complete carbon-line with no other variables.

It has been stated time and again by experienced steel-makers that the best steel, the most reliable under all circumstances, is that which comes nearest to pure iron and carbon.

Some intelligent steel-makers, and engineers cast doubts upon this statement, and assert that because phosphorus up to a certain limit, or manganese, or silicon, or in fact it may be said almost any element, added to dead-soft steel will give an increase of strength, therefore the presence of one or more of these elements is not only not harmful, but beneficial.

As a matter of fact, however, every one of these elements is harmful, either in producing cold-shortness, or red-short-

ness, or brittleness, and not one of them will add any good quality to steel that may not be obtained better by the use of carbon. Given a uniform minimum content of these impurities, the carbon-line may be depended upon to furnish any desirable quality that is obtainable in steel; and it is certain, always sure, that that steel which is the nearest to pure carbon and iron will endure the most punishment with the least harm.

That is to say, that such a steel when overheated a little, or overworked, or subjected to any of the irregularities that are inevitable in shop practice, will suffer less permanent harm than a steel of equal strength where there is less carbon and the additional strength is given by any other known substance.

It is difficult to show this from testing-machine data, indeed it is doubtful if any such data exist, but experience in the steel-works, in the bridge- and machine-shops, and in the field proves it to be true. For further discussion of this question see Chap. X.

The effects of a small difference in phosphorus or in silicon contents are shown plainly and unmistakably in high-carbon steel, and not so plainly in low-carbon steel; but as there is no known hard and fast line that divides low steel, medium steel, and high steel, so there is no marked difference in their properties. The same rules hold all along the line, the same laws govern all of the way through.

There is no set of properties peculiar to low steel and another set peculiar to high steel; the same laws govern all, and differences are those of degree and not of law.

Given three samples of steel of the following compositions:

	No. 1.	No. 2.	No. 3.
Silicon	.02	.20	.02
Phosphorus	.01	.01	.02
Sulphur	.005	.005	.005
Manganese	.100	.100	.100
Carbon	1.100	1.100	1.100

A skilful worker, not knowing the composition of any, will pick them out invariably by tempering them and testing them with a hand-hammer and by inspecting the fractures.

He will pronounce No. 1 to be the best and the strongest in every way; No. 2 to be not quite as strong as No. 1, and more liable to crack from a little variation in heat; No. 3 to be not so strong as No. 1, and that it will not come quite as fine as either of the others, and, like No. 2, it will not stand as much variation in heat as No. 1.

Give a ton of each to a skilful axe-maker, from which he will make one thousand axes of each, and he will be sure to report No. 1 all right; No. 2 good steel, more loss from cracked axes than in No. 1.

No. 3 good steel, some inclination to crack; it will not refine as well as No. 1 and is not as strong.

This is no guess-work, nor is it a fancy case; it is simple fact, borne out by long experience.

Give a skilful die-maker one hundred blocks of each to be made into dies. He will not break one of No. 1 in hardening them; he will probably break five to ten of No. 2; and if he breaks none of No. 3—a doubtful case—he will find in use that No. 1 will do from twice to twenty times as much work as either of the others. If he is making expensive dies,—many dies cost hundreds of dollars

each for the engraving,—he will think No. 1 cheap at 25 cents a pound, and either of the others dear at 15 cents a pound.

In such steel, then, the absence of a few points of silicon, or of a point or two of phosphorus, is worth easily 10 cents a pound.

Now let the carbon in these three steels be reduced to 10, making them the mildest structural steel. The differences to be found in the testing-machine in tensile strength, elastic limit, extension, and reduction of area will be almost or altogether nothing; in forging, flanging, punching, etc., under ordinary conditions differences would not be observable; therefore there would be no practical difference in value. But let the silicon be raised to 30 or the phosphorus to 10,—the Bessemer limit,—or let both be raised together, and both the testing-machine and shop practice would show a marked difference.

This shows that in the absence of carbon the action of these elements is sluggish as compared to their effects in the presence of high carbon, or in the low-carbon steels their effects are not so observable. That their influence is there, there can be no doubt, but if it be not enough to endanger the material it is not worth while to take it into account.

Is it safe and wise, then, for steel-users to ignore composition?

Users of tool-steel may do so safely, because the smallest variations will manifest themselves so unmistakably that they give immediate warning, and the steel-maker must keep his product up to a rigid standard of excellence or lose his character and his trade. Many of the ablest users of structural steel take a similar ground, and say, We

have nothing to do with method or composition if the material meets our tests.

It is believed that if these men knew how easy it is for a skilful worker to doctor temporarily an off heat by a little manipulation, and how dangerous the same may become by a little off practice in the field, they would be convinced that some limits should be put upon composition, especially if they could realize that a reasonable specification would add nothing to cost, as competition would take care of that.

The reader is referred again to Chap. X on impurities.

V.

GENERAL PROPERTIES OF STEEL.

STEEL is very sensitive to heat. In general it may be stated that, starting with cold steel, every degree of heat added causes a change in size and in structure, until the limit is reached where disintegration begins. The changes are not continuous; there are one or two breaks in the line, notably at the point where we have what is called recalescence; this is a marked phenomenon and it will be considered later.

The effects of heat are permanent, so that it is a fact that every variation of temperature which is marked enough to be visible to the naked eye will leave a structure, due to that variation, when the steel is cold, which will be observable by the naked eye, and such structure, when not influenced by external force, such as by hammering or rolling, is as invariable and certain as is the structure of an ingot due to the quantity of carbon present.

This property furnishes what may be called the steel-maker's and the steel-user's thermometer. By its means the steel-maker can discover every irregularity in heating that may have been perpetrated by the operatives; so also the steel-user can decide whether the steel furnished him has been heated and worked uniformly and properly, and later he can tell whether those who have shaped this steel to its final forms have done their work properly. A thorough knowledge of this property is essential to a steel-

maker; until he possesses it he is not fit to conduct his business. It is of great importance to the steel-user, and every engineer should try to acquire a knowledge of it in order that he may not be fooled by the carelessness or rascality of those who have preceded him. The steel-maker acquires this knowledge by daily contact with the facts; the engineer does not have it forced upon him in this way, but he should seek opportunities of observation, which will be abundant in his earlier practice when he is sent upon inspection duty. Like the structure of ingots, this heat-structure cannot be illustrated on paper, and an attempt to do so would be misleading; attempts at description will be made in the hope that by their means the engineer will have a pretty good idea what to look for, and to know when his suspicions should be aroused.

In addition to the ocular observations mentioned it has been shown by specific-gravity determinations, and by delicate electrical tests through small ranges of temperature, that steel is as truly thermometrical as mercury.

Steel passes through or into four general conditions due to heat. First, in the cold state, it is a crystalline solid of no uniform structure, for its structure is influenced by every element that enters into it, and by every irregularity of heat to which it has been subjected.

Good steel may be described as having a bluish-gray color, uniform grain as seen by the naked eye, and little lustre. But it should have some lustre and a silky appearance. When it is right, a steel-worker will say it is "sappy," and that name, absurd as it may sound when applied to a metal, really expresses an appearance, and implies an excellence that it would be hard to find a better word for. If the structure be dull and sandy-looking, the steel-worker

will say it is "dry," and that term is as suggestive and appropriate as the word "sappy."

If the fracture be granular with bright, flashing lustre, the steel-worker will say it is "fiery," and again his term is expressive and proper.

It is perfectly safe to say that steel of a "sappy" appearance is good steel; but in order to know what it is it must be learned by observation, it cannot be described in exact terms.

It is equally certain that a "dry" fracture indicates a mean steel, a steel inherently mean,—too much phosphorus, or silicon, or oxides, or all combined,—and such a steel is incurable.

A "fiery" fracture indicates too much heat. It may be found in the best steel and in the poorest; it may be corrected by simply heating to a proper temperature. It shows that some one needs to be reprimanded for careless work.

If now an inquirer will take a piece of good steel of "sappy" fracture, and of "dry" steel of dull, sandy fracture of the same carbon, and will heat them say first to dark orange, then to bright orange, dark lemon, and so on, and examine the fractures after each heating, he will find a "fiery" fracture in the "dry" steel at a heat much below that which is necessary to make the "sappy" steel "fiery." This is one proof that good steel will endure more punishment than poor steel.

Cold steel is not plastic in the common acceptance of the word; strictly speaking it has some plasticity, as shown in the extension noted in pulling it; this is its measure of ductility.

Also it may be drawn cold to fine wire of only a few

thousandths of an inch in diameter, and it has been rolled cold to one five thousandth of an inch thick. But this work must be done with great care; the steel soon becomes brittle, and a little overdrawing or overrolling will crush the grain and ruin the steel; therefore the work must be done a little at a time, and be followed by a careful annealing.

To reduce a No. 5 wire rod to .005 inch diameter will require with high steel suitable for hair-springs about fourteen annealings.

A skilful hammerman will take a piece of mild cold steel, and by means of light, rapid blows he will heat it up to a bright lemon heat without fracturing it; then he will have it thoroughly plastic and malleable.

This has no practical commercial value; it is a beautiful scientific experiment exhibiting high manual skill, and showing that there is no hard and fast line between non-plasticity and plasticity.

The first condition, then, is cold steel, not plastic, not malleable.

When steel is heated, it begins to show color at about 700° to 800° F.; the first color is known as dark cherry red, or, better, orange red; above this color it turns to a distinct, rather dark, or medium orange color; this is the heat of recalescence, a good forging-heat, and the best annealing- and quenching-heat. At this heat and above it good steel is truly plastic and malleable; a roller or hammerman will say, "It works like wax," and so it does.

This is the second or *plastic* condition.

Heated above this plastic condition to a bright lemon in high steel, or to a creamy, almost scintillating, heat in mild

steel, steel will go to pieces under the hammer or in the rolls; the workman will probably say it is burned, but it is not burned necessarily; it is simply heated up to the third or granular condition; it is the beginning of disintegration and the end of plasticity.

This granular condition is important in several ways. It is made use of in Sweden, and has been demonstrated in the United States, to determine the quantity of carbon in steel. An intelligent blacksmith is given a set of rods of predetermined carbon, ranging from 100 carbon to zero, or through any range that may be necessary; each rod is marked to indicate its carbon. He takes the rods one by one and heats them until they scintillate, well up into the granular condition, then lays them on his anvil and hammers them, observing carefully the color at which each one becomes plastic as it cools slowly. After a little practice he is given rods that are not marked, and by treating them in the same way he will give them their proper numbers, rarely missing the carbon by as much as 10 points, or one temper.

It is a beautiful and useful illustration of the effect of carbon. The rule is, the higher the carbon the lower the granulating-point; or, as is well known, high steel will melt at a lower temperature than low steel.

This shows that every temper of steel has its disintegration temperature where it passes from plastic to granular, as fixed as its fusion-point or its point of recalescence.

Steel passes from the granular condition to the *liquid* or fourth form.

There is little of interest in the liquid condition of steel to any but the steel-maker; what there is to be said will be mentioned later.

Steel in cooling from the liquid passes through the granular and the plastic conditions to the cold state.

The granular form is of special interest to the steel-maker for the reason that in this condition the steel has more of adhesion than cohesion; it will stick to anything it touches, and so cannot be made to flow. This is the cause of "bears," "stickers," and many of the troubles of the melter. Therefore steel must be put into the moulds while it is still molten, and moulds should be well smoked or lime-washed to prevent stickers. This condition is of great interest to engineers, because the failure to roll or shape molten steel by pouring it directly between the rolls is doubtless due to this adhesive, non-cohesive condition.

To produce sheets, bars, and all sorts of shapes from molten steel direct, without the expense of making, handling, and re-heating ingots, is an enticing idea which has occupied the minds and efforts of many able mechanics and engineers.

If steel passed directly from the liquid to the plastic condition as glass does, hammers and rolls would soon be replaced by dies at a great saving of cost and labor. It is no wonder that such a desirable end has led to many persistent and costly efforts, but until some way can be devised to eliminate this granular form in cooling it would seem that all such efforts must end in failure.

As steel cools down through the plastic condition the cooling is not continuous; there are two or three points where it is arrested for a time, and at one notable point the cooling is not only arrested, but after a few moments of stop the operation is reversed, the steel becomes visibly hotter, and then the cooling goes on regularly; there may

be other slight pauses, but they are of little importance compared to this one, which is known as the point of *recalescence.* There are many theories of the cause of this recalescence; the ablest scientists are still working at it; and until some definite conclusion is reached it is not worth while to write pages of discussion which may be found fully stated and illustrated over and over again in the various technical journals, and transactions of different engineering societies.

There are some properties of steel of great interest which seem to cluster around this recalescence-point; they will be noted as they are reached.

We have seen that there is a marked, definite structure of the grain of ingots due to every quantity of carbon, and also that there is a fixed limit of malleability for every quantity of carbon. It is known also that the recalescence-point shifts slightly with a change of carbon, and that it is much more marked and brighter in high-carbon steel than in low.

There are no other sure indications of the quantity of carbon present. As soon as an ingot is heated up to orange color, or the recalescent-point, it loses its distinctive structure and its fracture no longer furnishes a sure guide.

If three ingots of say, 20, 80, and 120 -carbon respectively be heated to orange and then cooled slowly, their fractures will be so different as to enable an expert to place them properly in their order of carbon, and to classify them as mild, hard, and harder; beyond that he could not go; if he attempted to give them their temper numbers, he would be likely to miss by four or five numbers either way, and a correct mark would be only a lucky guess.

Hammering and rolling heated steel affect the grain or structure profoundly; a high steel may be worked so that the grain will look mild, and a mild steel may be so worked that the grain will look hard. It is common to see a bar of steel with a fine grain at one end and a coarse grain at the other, and this state of things often frightens a consumer, who imagines that he has received a very irregular, uneven article, and he is as often astonished when it is shown to him that at the same proper heat the two ends will refine and harden equally well, and be exactly alike. In such a bar one end has been finished a little hotter than the other, and the grain is due to the heat in each case. This uneven heating may have been incidental or careless; with skilful workers it is rare.

One end might have been finished so cold as to crush the grain, and the other end so hot as to cause incipient disintegration, but a competent inspector would discover either condition at once and reject the bar.

There is, then, a specific structure due to temperature; it is modified by carbon and by treatment under the hammer or in the rolls. If a bar of steel be heated up to the highest plastic limit, just so that it will not fall to pieces, and then cooled slowly without disturbance, and a fracture be taken, it will be found to be coarse and with an exceedingly brilliant lustre. Now let it be heated again to a bright lemon color, but still plastic, and cooled as before; it will be found to be coarse, with bright lustre, but neither so coarse nor so bright as the first piece. Then let it be treated in this way to lemon color, light orange, medium orange, dark orange, and orange red; as the heats go down the grain will be finer and the lustre will be less, until at about medium orange the lustre will be absent.

If any number of bars of even composition be heated in this way, the fractures will all be alike for each temperature.

If a series of bars of the different full tempers, about seven in all, be treated in this way, the structures due to a given temperature will all be similar, but there will be no two exactly alike, because high steel is much more profoundly affected by heat than low steel.

Seven tempers are mentioned here, because that is the number of full tempers in common use. Steel is graded out into fifteen tempers ordinarily by the interpolation of half numbers; this is easy and sure in the ingot inspection. In the above experiment the differences due to carbon are not quite so delicate, and the work is hampered in the heating by the personal equation, so that the use of seven full tempers is refinement enough. There is a difference due to every separable quantity of carbon, which could be shown if all of the operations of the experiment were exact.

If when a bar is broken cold the fracture is uneven, with coarse grain in one part and fine grain in another, it shows that there has been uneven heating. If one side has large grain and the other side is fine, the bar has been a great deal hotter on the side having coarse grain than on the other: the heater has let the bar lie in the furnace with one side exposed to a hot flame and the other protected from the flame in some way; he has neglected to turn the bar over and heat it evenly.

If the outside of the bar is fine and the centre is coarse, the bar has been very hot all through and has been finished by light blows of the hammer or by light passes in the rolls; it has been worked superficially and not thoroughly.

If the outside of the bar is coarse and the centre is fine, the steel has been heated on the surface too hot and too quickly; it has not had time to get hot through, and it has had too little work in the finishing.

If the grain is dark, with the appearance of a rather heavy india-ink tint, the steel has been finished too cold, and it will be found to be brittle.

If the grain is very dark, especially about the middle, looking almost black, then it has been finished altogether too cold: the grain is disintegrated, and the bar is fit only for the scrap-heap.

A bar of this kind containing enough carbon to harden will harden thoroughly, and often appear to be sound and fine, but it is not sound and will not do good work; if it be brought up to a proper heat and forged to a point, it will almost certainly burst, showing that the integrity of the steel has been destroyed.

If a bar, or plate, or beam shows cracks on the surface or at the corners, with rough, torn surfaces, the steel has either been superficially burned or it is red-short. In either case it should be rejected, for the cracks, although small, will provide starting-points for ultimate fractures, whether it be tool-steel that is to be hardened, or structural steel that is to be strained without hardening. If the steel is to be machined, so that all of the cracks can be cut out, then in machinery-steel the removal of these surface defects might leave the finished piece sufficiently sound and good. If, however the steel is to be hardened, and the defects should be due to red-shortness, the piece would almost certainly break in the hardening; and if it were not red-short, then unless the cracks were cut away entirely, if the least trace of the crack is there, although

it may not be visible, that trace will be sufficient to start a crack when the piece is hardened.

EFFECTS OF COOLING.

Increase of heat causes increase of softness up to the liquid condition.

Decrease of heat—cooling—increases hardness up to the hardness of glass.

As an invariable rule the rate of cooling fixes the degree of hardness to be had in the cold piece within the limits of obtainable hardness or softness.

Slow cooling retains softness, so that when annealing is to be done the slower the cooling the better. Cooling is always a hardening process, but when it is carried on slowly more softness, will be retained than when the cooling is quick.

Rapid cooling produces hardness, and the more nearly instantaneous it is the greater the hardness will be. This property of hardening is of such extreme importance that it will be treated fully in a separate chapter.

There is an apparent exception to this rule shown in the operation called water-annealing. It is common, when work is hurried, to heat a piece of steel carefully and uniformly up to the first color, that is, until it just begins to show color, and then to quench it in water.

This is called water-annealing; and many believe that because a piece so treated is left softer than it was before treatment, the water-cooling had something to do with it. The fact is that hammering and rolling are hardening processes. When the increment of heat due to the work is

less than the decrement of heat due to radiation, the compacting of the grain increases hardness.

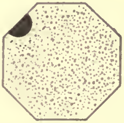
This process leaves the piece harder than does the quenching in water-annealing; the decrease in hardness due to water-annealing is the difference between the effects of the two operations. Let two pieces of the same bar be heated exactly the same for water-annealing; let one be quenched in water, and the other be allowed to cool in the air in a dry place. Then the superior softness of the air-cooled piece will show that the so-called water-annealing furnishes no exception to the rule.

There is one extremely important matter connected with cooling that should be noted carefully.

It is a common practice among steel-workers when they get a part of a piece of steel too hot to partially quench that part, and then go on with their heating; or if they are in a hurry to get out a big day's work, or if the weather is hot, and a pile of red-hot bars is uncomfortable, to dash water over the pile and hurry the cooling.

This practice means checks in the steel, hundreds of them.

A bar breaks and has this appearance. The dark spot is



the check; it did not show in the bar, no inspector could see it, but it broke the bar. Any one can prove this to his own satisfaction in a few minutes. Take a bar of convenient size, about one inch by one eighth; heat it carefully to an

even medium orange color and quench it completely; then snip it with a hand-hammer over the edge of an anvil, snipping away until satisfied that it is sound steel. There are no checks.

Now heat a similar length of the same bar in the same way, and pass it through the stream from the bosh-pipe, or submerge it for a moment in the bosh, not long enough to produce more than the slightest trace of a change in the color; then put it back in the fire and bring it gently to the uniform color used before, and quench it completely. Now when it is snipped over the anvil it will show numerous checks, dozens of them.

In this experiment the complete submersion for a moment may not produce checks at every trial, because the complete submersion permits practically uniform cooling, which if continued to complete cooling would be simply the ordinary hardening process. Still it will produce checks in the majority of cases, indicating that starting the changes, strains, or whatever they are of the quenching process and then stopping them suddenly while the steel is in the plastic condition does cause disintegration, so that the operation is dangerous and should not be tolerated. Passing the hot steel through a stream of water or dashing water over it must cause different rates of cooling, and necessarily produce local strains resulting in checks. These latter ways of injuring, therefore, rarely fail to produce the ruinous checks.

If this positive destruction is produced in this way, in steel containing enough carbon to harden it is clear that similar, although not so pronounced, results will be produced in the mildest steels when they are treated in the same manner.

The rule, then, should be: Never allow water to come in contact with hot steel, and never allow hot steel to be laid down upon a damp floor.

Even the spray from water which is run upon roll-necks may cause these checks in steel that is passing through the rolls, so that it is better to put up a guard to deflect such water away from the body of the roll.

A hammerman may sweep a bar with a damp broom to cause the vapor to explode with violence when the hammer comes down, and so tear away all rough scale and produce a beautiful finish. A careful, skilful man may be permitted to do this, but as surely as he gets his broom too wet, so that drops of water will fall on the steel and whirl around in the spheroidal condition, just so surely will he check the steel.

The best way is to have the broom not wet enough to drip, and then to strike it up against the top die when it is ready to descend; sufficient moisture will be caught upon the die to cause a loud explosion when it strikes the hot steel; it is a violent explosion and will drive off every particle of detachable scale, leaving as beautiful a surface as that which is peculiar to Russia sheet iron.

It is common in rolling tires to run jets of water over the tire to break up the scale and produce a clean surface. Tire-makers assert that experience shows that the water does no harm. There are two reasons for this if it be true: first, the steel is of medium carbon and more inert than high steel, and it has been hammered and compacted before rolling; second, the tires are usually turned, and this would cut away any little checks that might occur on the surface.

The magnetic properties of steel are well known. Soft

steel, like soft wrought iron, cannot be magnetized permanently; higher carbon steel will retain magnetism a long time, and hardened steel will retain it still longer. Hardened-steel magnets are the most permanent.

The permanency and the efficiency of a magnet increase with the quantity of carbon up to about 85 carbon; steel of higher carbon than this will not make magnets of so good permanency. The efficiency of a magnet of 85 carbon is increased largely by the addition of a little tungsten; a little less than .05% is sufficient.

It has been shown that tungsten has the property of retaining the hardness of steel up to a relatively high temperature; this additional power of retaining magnetism may indicate a close relation between the conditions set up by magnetism and by hardening.

It has been stated that maximum physical properties, except as to compression, are found at from 90 to 100 carbon; now we find maximum magnetic properties in the same region. Prof. Arnold has found by microscopic tests the same point of saturation; he fixes it at 89 carbon and deduces from it an unstable carbide of $Fe_{24}C$.

The magnetic maximum was found by magnet-makers by actual use in large numbers of magnets. Prof. J. W. Langley found the same maximum in a series of careful and delicate experiments undertaken to determine the best composition and the best treatment for the production of permanent magnets. Magnetism is affected by temperature, and it is found that steel becomes non-magnetic at or about the point of recalescence. This is important to electricians, as it marks the limit of temperature that is available to them. It is of interest to the scientists, as it is another indication of the importance of the changes that

take place at this temperature. Later, recalescence will be found to be an equally important point to the steel-worker, especially to the temperer

It has been stated that if a bar of steel be heated to any visible temperature and then be cooled without disturbance there will be a resulting grain or structure that is due to the highest temperature to which the bar was subjected. As a rule the highest temperature leaves a grain that appears to the eye to be the largest, or coarsest, whether the microscope shows it to be composed of larger crystals or not.

Let the following squares represent the apparent sizes of the grains:

1. The natural bar, untreated
2. Grain due to dark orange or orange red.
3. " " " medium orange
4. " " " bright orange
5. " " " dark lemon
6. " " " medium lemon
7. " " " bright lemon
8. " " " very bright lemon, or creamy.

These designations are used because steel in cooling down, or in heating up, runs through a series of yellow tints, not reds. It is common to see the expression "glowing white" applied to steel that is not even melted, when as a matter of fact melted wrought iron is not quite white. An occasional heat of steel may be seen that could fairly be called white, and then the melter knows that it is altogether too hot, and that he must cool the steel or make bad ingots.

"Glowing white," like "cherry red," will do for ordinary talk, but not for accurate description, although "cherry red" comes nearer to describing the dying color than "glowing white" comes to describing the highest heat.

An arc light may be "glowing white," and sunlight is "glowing white," and when either light falls upon melted steel it shows how far the steel is from being "glowing white."

Referring to the squares: If a bar that has been heated to No. 8 be re-heated to No. 2 and be kept at that color a few minutes to allow the steel to arrange itself, in other words, to provide for lag, and then be cooled, it will be found to have grain No. 2. Sometimes in performing this experiment the fracture will be interspersed with brilliant spots as if it were set with gems; this shows that not quite enough time was allowed for lag. Another trial with a little more time will bring it to a complete No. 2 fracture. If now it be heated to No. 4, or 5, or 6 in the same way, it will be found to have when cold the grain due to No. 4, or 5, or 6 temperature.

This may be repeated any number of times, and the changes may be rung on all of the numbers, until the disintegrating effect of numerous heatings begins to destroy the steel. This property of registering temperature, this steel thermometer, is of great value, and it will be referred to frequently.

EFFECTS OF MECHANICAL WORK.

When an ingot is heated and then hammered, rolled, or pressed hot, its density will be increased, as well as its strength when cold under all strains.

If it be hammered carefully, with heavy blows at first,

and with lighter and quicker blows at the last, the grain will become very close and fine; it is called "hammer-refined."

When down to the so-called cherry red, orange red, great care is needed, and when black begins to show through the red much caution must be used; any heavy blows will crush the grain and produce the dark or black color mentioned before.

Fine-tool makers attach great importance to this hammer-refining; some of the most expert will not have a rolled bar if a well-hammered one can be had. At first thought this would seem to be a mere notion, but the testimony in favor of hammering is so universal among those who know their business that it would seem as if it must be based upon some reason. If it have any scientific basis of fact, it is that the shocks or vibrations of the hammer keep the carbon in more intimate union with the iron, whether it be combination or solution, than either rolling or pressing will do. After considering the phenomena of hardening, tempering, annealing, etc., it may be concluded that there is something in this. It is easy to laugh at and to deride shop prejudices, and there are enough of them that deserve ridicule; again, there are some that will not down, and they compel the scientist to hunt for explanations. But after all, ridicule is dangerous; it is possible that a careful comparison of some of the laws laid down by the highest scientists would tend to excite the risibles. If the hand-worker sometimes flounders in the mud, the scientist is sometimes enveloped and groping in mist.

Hot-rolling produces results similar to those of hot-hammering; it makes the grain finer, increases density, and adds to the strength.

The same precautions are needed in rolling as in hammering. Heavy passes with rapid reduction may be used to advantage while the steel is hot and thoroughly plastic; as the heat falls the passes should be lighter to avoid crushing the grain.

Overrolling, like too much hammering, may be more injurious than too little work; a coarse, irregular structure due to too little work may be rectified and made fine and even by annealing, while if the grain be crushed by overwork the damage cannot be cured by annealing; the annealed grain may appear to be all right, but on testing, the strength will be found impaired.

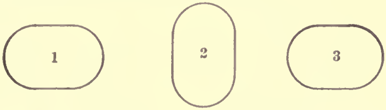
By care and light passes steel may be rolled safely down to a black heat and be made elastic and springy. It is common to roll spring-steel in this way so that it may be formed into a spring and have all of the properties of a tempered spring without going through the operations of hardening and tempering. This is often desirable for spring-makers, as it saves them considerable expense; but it is hazardous work, because it is so difficult to heat every piece exactly to the same temperature, and secure every time the same number of passes and the same pressure in each. The best roller will get some pieces too hard and brittle, and some too soft and ductile. A careful steelmaker will shun such work.

Cold-hammering, cold-rolling, and cold-drawing reduce specific gravity and increase tensile, transverse, compressive, and torsional strength. They increase hardness and brittleness, reducing ductility. The hardness due to cold-working is different from that due to hot-work or quenching; the latter operations produce great elasticity as well as hardness.

The hardness due to cold-working might be described as harshness; the steel is not truly springy; of course it will bend farther without permanent set than an annealed piece, but it never has the true spring elasticity. If it be worked far enough to be really springy, it will bear the same relation to a hot-worked spring that a piece of cross-grained, brashy oak bears to a piece of well-seasoned, straight-grained hickory.

The hammering of round sections between flat dies tends to burst the bars in the centre; great care must be used to avoid this, and the most skilful and careful hammermen will often turn out bursted bars. The bursts do not show on the surface; the bars are true to size, round, smooth, and sound on the outside. The safest plan is to hammer in a V-die, or in rounded swedges.

Radial rolling will produce the same results, and it is on this principle that the celebrated Mansmann tubes are made. The explanation seems to be simple, as the following exaggerated sketches will show:



No. 1 has been struck; it is then turned up to position No. 2 and knocked into shape No. 3. The rapid hammering of a bar, turning it a little at a time, must burst it if the blows are heavy enough to deform the whole section. Heavy radial rolling produces the same results.

The concluding pages of this chapter will be devoted to a few examples showing by tests the effects of heat and work upon specific gravity, tensile strength, elasticity, and

ductility; they are not to be taken as fixing exact limits in any case; they are given merely to illustrate the truth of the general properties stated, and to show the wide ranges of strength that are attainable by varying carbon and work.

TABLE I.

Crucible Steel.	Ingot Numbers.											
	1	2	3	4	5	6	7	8	9	10	11	12
Carbon......	.302	.490	.529	.649	.801	.841	.867	.871	.955	1.005	1.058	1.079
Silicon. ..	.019	.034	.043	.039	.029	.039	.057	.053	.059	.088	.120	.039
Phosphorus .	.047	.005	.047	.030	.035	.024	.014	.024	.070	.034	.064	.044
Sulphur.....	.018	.016	.018	.012	.016	.010	.018	.012	.016	.012	.006	.001
Sp.gr. ingots.	7.855	7.836	7.841	7.829	7.838	7.824	7.819	7.818	7.813	7.807	7.803	7.805
Sp. gr. bars, burned, 1..	..	.....	7.818	7.791	....	7.789	.....	7.752	....	7.744	....	7.690
2..	....	....	7.814	7.811	....	7.784	....	7.755	.....	7.749	. ..	7.711
3..	.. ..	.....	7.823	7.830	.. .	7.780	... .	7.758	.....	7.755	.....	7.769
4..	....	.....	7.826	7.849	....	7.808	.....	7.773	.....	7.789	....	7.798
5..	....	.....	7.831	7.806	....	7.812	. ..	7.790	.....	7.812	.....	7.811
cold, 6......	.....	....	7.844	7.824	....	7.829	....	7.825	.....	7.826	.....	7.825
Diff. 6-1.. ...	.. .	.....	.025	.034	.....	.040	....	.073	.....	.082	.....	.135
Mean diff. of carbon	.071	.. .	..	....	..	.. .	....	... .	.....	....	.....	......

The twelve ingots treated here were first selected by ocular inspection for carbons; the carbons were then determined by combustion analyses.

It will be seen that the inspection was correct, and that the mean difference in carbon between consecutive numbers is .007. Between Nos. 7 and 8 there is a difference of only .004 ; when the analyst discovered this, he asked for a reinspection, not giving any reason for his request. The inspectors made new fractures, examined the ingots carefully in good light, and reported that they erred the first time, that both ingots belonged in the same temper number, but that if there were any difference No. 8 was the harder. It is not claimed that a difference of .004 is really observable.

The contents of silicon, phosphorus, and sulphur show clearly that the controlling element is carbon. This ex-

periment has been repeated a number of times, and always with the same result, showing that there is no uncertainty in this method of separating tempers.

Parts of these ingots were reduced to ¾-inch round bars. The specific gravities of the ingots were taken, showing generally a reduction of sp. gr. for an increase of carbon. No. 3 and 5 are anomalous; an explanation of this could doubtless have been found if a careful investigation had been made, but there was no re-examination.

The sp. gr. No. 6 are of the ¾-inch bars as they came from the rolls; they are all heavier than the ingots except No. 4, and they are of nearly uniform sp. gr.; this is due doubtless to the fact that the higher carbon steels are so much harder than the low-carbon steels that it required much more work to reduce them to the bars, and as hot-working increases density, the densities of the higher carbons were increased more than those of the lower.

The bars were nicked six times at intervals of about ¾ inch and then heated so that the ends were scintillating, ready to pass into the granular condition, and the heat was so regulated as to have each piece less hot than the piece next nearer to the end, the last piece, No. 6, being black and as nearly cold as possible.

It is manifest that this operation is subject to the error of accidentally getting No. 2, for instance, hotter than No. 1, and so on, so that perfect regularity is not to be expected; to obtain a true rule of expansion it would be necessary to make hundreds of such experiments and use the mean of all.

It will be noticed that No. 4 is abnormal in the ingot series, and that the No. 6 piece of No. 4 is abnormal in being lighter than the ingot; probably this No. 6 of No. 4

was hot when it was intended to be cold. Also No. 2 of ingot No. 3 is lighter than its No. 1, showing another irregularity in heating.

Taking the whole list of No. 1 pieces, they are all lighter than their respective No. 6 pieces; the differences of sp. gr. 6–1 are progressive, being only .025 for the No. 3 ingot and .135 for the No. 12 ingot. This shows clearly that expansion due to a given difference in temperature is much greater in high steel than in low steel.

This clears away the mystery of the so-called treachery of high steel, its tendency to crack when hardened. There is no treachery about it; it is very sensitive to temperature, and it must be treated accordingly.

A few examples will now be given to show the changes of tensile strength, ductility, etc., that may be had by differences of carbon, and by differences of treatment, annealing, hardening, and tempering.

TABLE II.

Character of Steel.	O. H.	Crucible Sheet	O. H.	O. H.	O. H.	Crucible Eye-bar, 2″ × 1″.	Crucible Eye-bar. 2″ × 1″.	Crucible Eye-bar, 2″ × 1 .	Crucible ½-in. Drawn Wire.
Carbon......	.09 to .12	.435	.50	.60	.70	.96	1.35	1.40	1.15
Silicon.........	.008	.014	.025	....	......	.156	....	....	< .02
Phosphorus.. .	.007	.050	.016	....	.. ...	.008	....	....	< .02
Sulphur........	.026	.023	.028	...	......	.015	....	....	trace
Manganese ...	.055	.204	.325	.. ...	......	.24	....	....	< .30
Tensile str'gth, lbs. per sq.in.	46800	73142	84220	108800	117400	124800	100733	117710	141500
Elastic limit...	30900	.....	62560	71500	69980	65000	85078	69850	92420
Elongation...	in 2 in. 41%	in 1 in. 42%	25%	14.5%	11.5%	4.75%	.5%	7.28 at 2.85 in 2½	2%
Reduction of area........	75.85%	62.3%	29.91%	13.55%	8.59%	......	....	13.03%	2.42%
Fracture.....	silky ½cup	......	.. .	.....	....	broke in neck slight flaw, fine grain	broke in head close grain	....	broke in grip

O. H. is the abbreviation for open hearth.

Second column is mean of 24 analyses and 24 tests of boiler-sheets.

TABLE III.

Cold-drawn Wire, ½-inch Diam.	Tensile Strength, lbs. per sq. in.	Elastic Limit, lbs. per sq. in.	Elongation.		Reduction of Area, per ct.
			In 3 in.	Per cent.	
Cold-drawn, broke in grip	141,500	92,400	.06	2.00	2.42
Same bar drawn black	138,400	114,700	.18	6.00	12.45
" " annealed	98,410	68,110	.30	10.00	11.69
" " hardened and then drawn black	248,700	152,800	.25	8.33	19.7

Analysis of this bar is given in Table II in the last column.

A test of ½-inch wire to show effect of cold-drawing, tempering, annealing, and hardening and tempering. Four pieces were cut from the same bar. It is probable that the first piece would have given a little higher tensile if it had not broken in the grip; it was clamped too tight. The second piece was heated until it passed through all of the temper colors and turned black, technically called "drawing black," or drawing out all of the temper. It is not quite annealing; the idea was to find the effect of temper-drawing upon a cold-hardened drawn wire.

The effect of this operation was to lower the ultimate and raise the elastic strength, increasing also the ductility.

The third piece was heated carefully to the recalescence-point, and cooled slowly, thus annealing it completely, and giving the normal strength of a bar of this composition.

The fourth piece was heated to recalescence and quenched, hardening and refining it thoroughly; it was then tempered through all of the colors until it turned black; the result shows the enormous potencies there are in the hardening and tempering operations.

The cases given in Table II were selected indiscriminately, so as to show better the effect of carbon, as we here

have tests of ordinary test-bars, boiler-sheet, small eye-bars, and drawn wire.

The 96-carbon eye-bar and the 115-carbon $\frac{1}{2}$-inch wire are the nearest to the 100-carbon saturation limit mentioned before, and they show the highest strength. The 96-carbon eye-bar had a slight flaw in the fracture, which doubtless caused it to break below its real strength.

The 135-carbon eye-bar broke in the head in a way to indicate that there was some local strain there, due to forging.

These examples are not given as establishing any general law; they are illustrations of what all experience shows to be the fact, that the strength of steel is affected profoundly by the quantity of carbon present, and also by heat and by mechanical work. From 46,800 lbs. to 248,700 lbs. tensile strength per square inch is an enormous range, and these figures probably represent pretty closely the ultimate limits at present attainable.

An inspection of the analyses makes it clear that the other elements present in addition to carbon were not there in sufficient quantity or variety to have had much effect upon the results.

VI.

HEATING FOR FORGING; FOR HARDENING; FOR WELDING.

BURNING, OVERHEATING, RESTORING.

FROM what has been said already about the effects of heat it follows without further argument that heating is one of the most important, or perhaps more properly the most important of all, of the operations to which steel has to be subjected.

The first and vital thing to be borne in mind is that all heating should be uniform throughout the mass. It has been shown that heat affects the grain, the structure, as surely as it moves the mercury-column, and such being the case it is plain that as perfect uniformity as it is possible to attain is the first essential for all heating, no matter what the ultimate object may be.

In heating for forging the limit lies between the point of recalescence, the beginning of true plasticity, and the granular condition, the end of plasticity; these temperatures lie between dark or medium orange for all steels and medium or light lemon on the upper limit, depending on the carbon content, or lower if it be an alloy steel.

If there is much work to be done upon a piece of steel, it is well to heat at first to as high a temperature as is safe, and then to forge or work heavily at the higher heat,

reducing the blows or passes as the piece is reduced and the temperature falls. Although this high heating will raise the grain of the steel, the heavy working will bring it back to a fine, compact structure.

If little work is to be done, then it is better to heat as low as may be safe, and allow the work to be done without letting the heat down below orange red, so that the steel may not be crushed in the grain.

Below orange red, the so-called "dark cherry," steel should not be forged, except that in forging for fine tools it is well to give many light and rapid blows until black begins to show in order to hammer-refine it; this must be done with extreme care so as not to crush the steel and cause cracking in the subsequent hardening, or crumbling in the hardened tool.

HEATING FOR HARDENING.

When a piece of steel is to be hardened by quenching in water or any quick-cooling medium, it should be heated with great care to the exact temperature to produce the required hardness.

After forging, no piece of steel should be quenched without first being heated uniformly to the proper temperature. Ede in his book recommends quenching immediately after forging in some cases. The so-called Harvey patent recommends cooling from a high heat down to the required heat and then quenching.

Both practices are bad. In the Ede case this is believed to be the only bad piece of advice in his very valuable book—in every other respect the most practical and useful book upon the manipulation of steel known to the author.

The reason for objecting to the quenching after forging

without re-heating is that forging always sets up uneven strains in the mass; the flow is easier from the sides than from the middle of the piece, and therefore the amount of work done upon one part is greater than upon another; also it is impossible to hammer or press a piece of steel with exact uniformity throughout, so that it follows that after forging there is never exact uniformity of texture or temperature, and such uniformity is the one essential thing to insure good and even hardening.

The practice of allowing a highly heated piece to cool down to a given color and then quenching is objectionable, because it produces a coarse and brittle grain due to the higher heat.

Referring to the illustration on page 67 of the squares representing grains due to different temperatures: Assume that square No. 3 represents the heat at which quenching is to take place, and No. 6 is the heat to which the piece has been subjected; then the piece when it has cooled to No. 3 will not have the grain due to No. 3 heat: it will have a larger, coarser grain that formed as the piece cooled from No. 6. If now it be quenched, it will have only the hardness due to No. 3, with a much coarser and more brittle grain than No. 3 heat should give. The way to manage such a case is to let the piece cool completely and assume the No. 6 grain; then re-heat carefully to exactly No. 3 and no hotter; keep the piece at that heat for a few minutes, or moments, according to its size, to allow for lag: then it will have the finer grain due to No. 3 heat, and when quenched it will be as hard as under the other method, and it will be much finer and stronger.

The same rule applies to any two temperatures.

As an expression of exactness as to evenness of heat, it

may be said that the piece should be as uniform in color as if it had been dipped into a pot of paint. When such uniformity is attained, a break from quenching is rare, unless the piece has been shamefully overheated so that the strains of quenching are greater than the tenacity of the steel.

HEATING FOR WELDING.

When an ingot is to be forged or rolled, it is well to take the highest heat possible—that immediately below the heat of granulation. Such a heat may be taken safely by keeping the steel covered with a surface flux to protect it from the flame. Ordinary red clay, dried and powdered, is an excellent flux for the purpose, and the cheapest known. Melted and powdered borax is the best of known fluxes, but it is so expensive that, as a rule, it is used only on the finest tool-steel, or on some of the alloy steels where the highest heat possible is not above a bright orange color, or hardly so high.

A good flux, intermediate in cost between common red clay and powdered borax, is an earth or mineral barite, or heavy spar. This material fuses more readily than red clay and not quite so easily as borax. It forms a good protective covering on the steel, and it is nearly or quite as efficient as borax.

The object in heating so high is to make the steel as soft and plastic as it may be, so that the subsequent working will close up all porosity as far as possible. Nearly all ingots have in them a greater or less number of cavities, commonly called blow-holes, that are caused by the separation of occluded gases during cooling. If such porosities are not oxidized on the surface they will disappear under heavy working at a high heat. It is probable that under

the compression of the work the gases are redisseminated in the mass and the walls of the cavities are reunited. If there be the slightest oxidation of the surface of a cavity the walls will not reunite: there will be left in the mass a little flat film of oxide which will prevent the union.

In mild steels used for machinery or structural purposes these little films may do no harm, the factor of safety being sufficient to more than cover any weakening effect. In tool-steel that is to be hardened such little films are almost certain to cause fracture. Dies as large as twelve inches square and six to eight inches thick, having been heated and quenched with the greatest care, have split fairly in two, and have revealed in the fracture a little film no larger than half an inch in diameter and of inappreciable thickness. At the same time the perfectly uniform grain and hardness showed that the highest skill had been used. This is only one illustration of the fact that every break in the continuity of the grain in steel forms a starting-point for fracture under heavy stress.

From what has been said it is plain that to weld two pieces of steel together is a difficult matter; still it can be done if great care be used. In general it is better to avoid such welding except in cases of necessity. The welding of steel tubing, and the electric welding of rails, frogs, switches, etc., is done on a large scale and satisfactorily, so that it will not do to say that steel cannot be welded. It can be welded or pasted together, and it is a good operation to avoid in all high steel. In case steel is to be hardened a weld will reveal itself almost certainly.

BURNING IN HEATING.

When a piece of steel breaks and shows a coarse, fiery fracture, it is common to say that it is burned. This is not necessarily the case. There are several degrees in the effects of heat. The first is the raising of the grain; the second, in high steel, is the decarbonizing or burning out of carbon from the surface in, the depth of the decarbonizing depending upon time and temperature; the third is oxidizing, or actual burning in the common acceptance of the term.

All of these operations go on to a slight extent every time a piece of steel is heated, but when the heating is done carefully there is only a small film of steel that is decarbonized and oxidized, and this film flies off when the piece is quenched for hardening. When the steel is forged or rolled this skin will be united firmly to the steel, and it will be thinner or thicker, according to the number of heatings and the time of exposure to the fire. In tool-making this skin must always be removed. Many an expensive tool is made perfectly worthless by not having this skin all removed, owing usually to mistaken economy. The steel is expensive, and the tool-maker does not wish to cut it up into worthless chips.

When a tool costing, say, twenty-five dollars is made useless by failure to cut away twenty-five cents' worth of useless skin, the economy of such an operation requires no discussion. It is impossible to forge a piece of steel without producing such a skin, and it is well known that decarbonized iron will not harden.

Ordinarily a cut of $\frac{1}{16}$ of an inch should remove such a skin on straight rolled or hammered bars. In the case of

a shaped forging where many re-heatings have been required the forgeman will have done good work if the cutting away of $\frac{1}{8}$ of an inch will present a good surface: tool-makers should consider this and allow for it. On the other hand, if a tool-maker finds that the removal of $\frac{1}{8}$ of an inch from a bar, or $\frac{1}{4}$ of an inch from a forging will not yield him a good, hard surface, he should hold the steel-maker responsible for bad work.

Actual burning reveals itself in rough tears, and cracks at the surface and corners of the piece. Such a piece should go to the scrap heap.

Overheated steel of coarse, fiery grain has been injured, and not necessarily destroyed. Such a piece may be restored to any fineness of grain by heating to the right temperature—medium orange for the best grain—keeping it at that heat for, say, one minute for a little piece, and five to ten or fifteen minutes for a large piece. The heat should penetrate the whole mass, and it should not be allowed to run above the given color in any part, not even for a moment. It should then be allowed to cool in a dry place, without disturbance. The grain will now be fine and uniform, and the steel may be worked in the ordinary way.

This simple operation is all that is necessary to restore to a fine grain any piece of steel that has been overheated, provided that the piece has not been actually burned nor ruptured.

VII.

ANNEALING.

It has been shown that the grain or structure of steel is profoundly affected by heat, so that any difference of heat-color that is visible to the naked eye will cause a difference of grain that is also visible to the naked eye.

Specific-gravity tests and delicate magnetic tests have proved that for every variation in grain there is a difference of specific gravity, which means, of course, a difference in volume; from this it is clear that if in any one piece of steel there exists a variety of grain due to uneven heating, there must necessarily be in the mass internal destructive strains. These strains become manifest when a piece of unevenly heated steel cracks in hardening; in this case the strains are greater than the tenacity of the steel.

It is well known, also, that all working of steel, such as forging or rolling, has a hardening effect, so that ordinary bars or forgings cannot be machined readily in the condition in which they are left by these operations.

If there were no remedy for these conditions of internal stress and initial hardness, the general use of steel would be very difficult, and its application would be limited seriously.

Fortunately, there are three properties of steel which furnish an easy and efficient remedy.

First, the fact that steel will assume by mere heating a grain or structure due to any temperature, no matter what its previous structure may have been, makes it a simple matter to remove practically all irregularities of grain and stress, by heating the mass to a perfectly uniform color and allowing it to cool uniformly.

Second, as heating is a softening process always, the mere heating of any piece of steel will soften it, and the amount of this softness that can be retained when the piece is cold is a direct function of the length of time of cooling, so that by sufficiently slow cooling any steel can be left reasonably soft.

This does not apply to Hadfield's manganese steel, which cannot be made soft when cold by any of the known processes of annealing.

Third, by reference to the specific-gravity table No. I, Chap. V, it will be seen that the change in volume due to differences of temperature is much less in mild steel than in high steel. This fact does not rest upon the evidence of this table alone; it is a fact of common knowledge to all steel-makers that mild steel is much more inert than high steel; therefore differences of heat and working that produce serious results in high steel are hardly appreciable in mild steel. As a rule all structural steels are comparatively mild, therefore they are generally in a fit condition for use when they leave the rolls or forge. In cases of special forging, where one part is heated and another is left cold, as in the forging of the heads of eye-bars, it would seem to be wiser to anneal such pieces to remove the area of strain that must exist between the unheated parts and those that were heated and forged.

The operation of removing strains and hardness by

careful, uniform heating and slow cooling is known as *annealing.*

Annealing should not be confused with tempering. Tempering is the partial softening of hardened steel, to remove some of the exceeding brittleness of hardened steel, and so to make it strong and highly elastic while it is still very hard.

Annealing is the complete softening of a piece of steel; that is to say, as a rule, the obtaining of the utmost softness that is possible; or in any case to have the steel softer than any tempering would leave it.

Annealing, and tempering are frequently used synonymously. Such misuse of terms in speaking of technical matters leads to confusion of ideas and misunderstandings.

As a rule, the best heat to use for annealing is that which gives a medium orange color; it is a good heat to quench from; it is a little above the heat of recalescence, about 655° Cent. This heat is that which gives the finest grain to steel when it is hardened, and is known as the refining heat.

As steel is thoroughly plastic and soft at this heat, and as it yields the best and strongest grain when cooled from this heat, it is clear that there is nothing to be gained by heating any higher for annealing.

In annealing, the steel should be brought up to the right color, medium orange, and left at that heat until it is hot through, care being taken that the heat does not run any higher in any part of the piece. If the corners or edges or any part be allowed to run up to bright orange, or to medium or bright lemon, as is often done, then there is bad work; the result will be uneven grain and internal strains.

When steel is to be hardened afterwards, there may be no harm in heating up to an even lemon color ; but where is the use in applying this excess of heat merely to make a coarse grain, when the lower, medium orange color will give just as good softness and a much better grain ?

The time necessary for good annealing depends upon the size of the piece ; a wire may be brought up to the right heat in five minutes or less, and heated through in another minute ; then it should be removed from the fire, as every additional moment of heating will only injure the steel.

A block six or eight inches cube may require three to five hours to bring it up to the color and have it heated through, and sufficient time should be given ; but as soon as it is hot through it should be removed from the fire.

A six-inch block may be brought up to a medium orange color in twenty minutes or less in a hot furnace, and then if it be kept in such a furnace until it is hot all through, the surface and edges will almost certainly be brought to a bright lemon color, with bad results. To do good annealing a piece should never be hotter in one part than in another, and no part should be hotter than necessary, usually the medium orange color. Annealing, then, is a slow process comparatively, and sufficient time should be allowed.

There are many ways of annealing steel, and generally the plan used is well adapted to the result desired ; it is necessary, however, to consider the end aimed at and to adopt means to accomplish it, because a plan that is excellent in one case may be entirely inefficient in another.

Probably the greatest amount of annealing is done in the manufacture of wire, where many tons must be annealed daily.

For annealing wire sunken cylindrical pits built of fire-bricks are used usually; the coils of wire are piled up in the cylinders, which are then covered tightly, and heat is applied through flues surrounding the cylinders, so that no flame comes in contact with the steel. For all ordinary uses this method of annealing wire is quick, economical, and satisfactory. The wire comes out with a heavy scale of oxide on the surface; this is pickled off in hot acid, and the steel should then be washed in limewater, then in clean water, and finally dried.

If it be desired to make drill-wire for drills, punches, graving-tools, etc., this plan will not answer, because under the removable scale there is left a thin film of decarbonized iron which cannot be pickled off without ruining the steel, and which will not harden. It is plain that this soft surface must be ruinous to steel intended for cutting-tools, for it prevents the extreme edge from hardening—the very place that must be hard if cutting is to be done.

Tools for drills, lathe tools, reamers, punches, etc., are usually annealed in iron boxes, filled in the spaces between the tools with charcoal; the box is then looted and heated in a furnace adapted to the work. This is a satisfactory method generally, because the tools are either ground or turned after annealing, removing any decarbonized film that may be found; the charcoal usually takes up all of the oxygen and prevents the formation of heavy scale and decarbonized surfaces, but it does not do so entirely, and so for annealing drill-wire this plan is not satisfactory. It is a common practice in annealing in this way to continue the heating for many hours, sometimes as many as thirty-six hours, in the mistaken notion that long-continued heating produces greater softness, and some people adhere

to this plan in spite of remonstrances, because they find that pieces so annealed will turn as easily as soft cast iron. This last statement is true; the pieces may be turned in a lathe or cut in any way as easily as soft cast iron, for the reason that that is exactly what they are practically. When steel is made properly, the carbon is nearly all in a condition of complete solution; it is in the very best condition to harden well and to be enduring.

When steel is heated above the recalescence-point into the plastic condition, the carbon at once begins to separate out of solution and into what is known as the graphitic condition. If it be kept hot long enough, the carbon will practically all take the graphitic form, and then the steel will not harden properly, and it will not hold its temper. To illustrate: Let a piece of 90-carbon steel be hardened and drawn to a light brown temper; it will be found to be almost file hard, very strong, and capable of holding a fine, keen edge for a long time.

Next let a part of the same bar be buried in charcoal in a box and be closed up air-tight, then let it be heated to a medium orange, no hotter, and be kept at that heat for twelve hours, a common practice, and then cooled slowly. This piece will be easily cut, and it will harden very hard, but when drawn to the same light brown as the other tool a file will cut it easily; it will not hold its edge, and it will not do good work.

Clearly in this case time and money have been spent merely in spoiling good material. There is nothing to be gained, and there is everything to be lost, in long-continued heating of any piece of steel for any purpose. When it is hot enough, and hot through, get it away from the fire as quickly as possible.

This method of box-annealing is not satisfactory when applied to drill-wire, or to long thin strands intended for clock-springs, watch-springs, etc.

The coils or strands do not come out even; they will be harder in one part than in another; they will not take an even temper. When hardened and tempered, some parts will be found to be just right, and others will have a soft surface, or will not hold a good temper. The reason of this seems to be a want of uniformity in the conditions: the charcoal does not take up all of the oxygen before the steel is hot enough to be attacked, and so a decarbonized surface is formed in some parts; or it may be that some of the carbon dioxide which is formed comes in contact with the surface of the steel and takes another equivalent of carbon from it. Whatever the reaction may be, the fact is that much soft surface is formed. This soft surface may not be more than .001 of an inch thick, but that is enough to ruin a watch-spring or a fine drill.

Again, it seems to be impossible to heat such boxes evenly; it is manifest that it must take a considerable length of time to heat a mass of charcoal up to the required temperature, and if the whole be not so heated some of the steel will not be heated sufficiently; this will show itself in the subsequent drawing of the wire or rolling of the strands. On the other hand, if the whole mass be brought up to the required heat, some of the steel will have come up to the heat quickly, and will then have been subjected to that heat during the balance of the operation, and in this way the carbon will be thrown out of solution partly. This is proven by the fact that strands made in this way and hardened and tempered by the continuous process will be hard and soft at regular intervals, showing that one side

of the coil has been subjected to too much heat. This trouble is overcome by open annealing, which will be described presently.

When steel is heated in an open furnace, there is always a scale of oxide formed on the surface; this scale, being hard, and of the nature of sand or of sandstone, grinds away the edges of cutting-tools, so that, although the steel underneath may be soft and in good cutting condition, this gritty surface is very objectionable. This trouble is overcome by annealing in closed vessels; when charcoal is used, the difficulties just mentioned in connection with wire- and strand-annealing operate to some extent, although not so seriously, because the steel is to be machined, removing the surface.

The Jones method of annealing in an atmosphere of gas is a complete cure for these troubles.

Jones uses ordinary gas-pipes or welded tubes of sizes to suit the class of work. One end of the tube is welded up solid; the other end is reinforced by a band upon which a screw-thread is cut; a cap is made to screw on this end when the tube is charged. A gas-pipe of about $\frac{1}{2}$-inch diameter is screwed into the solid end, and a hole of $\frac{1}{16}$- to $\frac{1}{8}$-inch diameter is drilled in the cap.

When the tube is charged and the cap is screwed on, a hose connected with a gas-main is attached to the piece of gas-pipe in the solid end of the tube; the gas-pipe is long enough to project out of the end of the furnace a foot or so through a slot made in the end of the furnace for that purpose.

The gas is now turned on and a flame is held near the hole in the cap until the escaping gas ignites; this shows that the air is driven out and replaced by gas.

The pipe is now rolled into the furnace and the door is closed, the gas continuing to flow through the pipe. By keeping the pipe down to a proper annealing-heat it is manifest that the steel will not be any hotter than the pipe. By heating the pipe evenly by rolling it over occasionally the steel will be heated evenly. A little experience will teach the operator how long it takes to heat through a given size of pipe and its contents, so that he need not expose his steel to heat any longer than necessary.

There is not a great quantity of gas consumed in the operation, because the expanding gas in the tube makes a back pressure, the vent in the cap being small. This seems to be the perfection of annealing. A tube containing a bushel or more of bright, polished tacks will deliver them all perfectly bright and as ductile as lead, showing that there is no oxidation whatever. Experiments with drill-rods, with the use of natural gas, have shown that they can be annealed in this way, leaving the surface perfectly bright, and thoroughly hard when quenched. This Jones process is patented.

Although the Jones process is so perfect, and necessary for bright surfaces, its detail is not necessary when a tarnished surface is not objectionable.

The charcoal difficulty can be overcome also. Let a pipe be made like a Jones pipe without a hole in the cap or a gas-pipe in the end. To charge it first throw a handful of resin into the bottom of the pipe, then put in the steel, then another handful of resin near the open end, and screw on the cap. The cap is a loose fit. Now roll the whole into the furnace: the resin will be volatilized at once, fill the pipe with carbon or hydrocarbon gases, and unite

with the air long before the steel is hot enough to be attacked.

The gas will cause an outward pressure, and may be seen burning as it leaks through the joint at the cap. This prevents air from coming in contact with the steel. This method is as efficient as the Jones plan as far as perfect heating and easy management are concerned. It reduces the scale on the surfaces of the pieces, leaving them a dark gray color and covered with fine carbon or soot. For annealing blocks or bars it is handier and cheaper than the Jones plan, but it will not do for polished surfaces. This method is not patented.

OPEN ANNEALING.

Open annealing, or annealing without boxes or pipes, is practised wherever there are comparatively few pieces to anneal and where a regular annealing-plant would not pay, or in a specially arranged annealing-furnace where drill-wire, clock-spring steel, etc., are to be annealed.

For ordinary work a blacksmith has near his fire a box of dry lime or of powdered charcoal. He brings his piece up to the right heat and buries it in the box, where it may cool slowly. In annealing in this way it is well not to use blast, because it is liable to force all edges up to too high a heat and to make a very heavy scale all over the surface. With a little common-sense and by the use of a little care this way of annealing is admirable.

It is a common practice where there is a furnace in use in daytime and allowed to go cold at night to charge the furnace in the evening, after the fire is drawn, with steel to be annealed, close the doors and damper, and leave the

whole until morning. The furnace does not look too hot when it is closed up, but no one knows how hot it will make the steel by radiation: the steel is almost always made too hot, it is kept hot too long, and so converted into cast iron, and there is an excessively heavy scale on it.

Many thousands of dollars worth of good steel are ruined annually in this way, and it is in every way about the worst method of annealing that was ever devised.

To anneal wire or thin strands in an open furnace the furnace should be built with vertical walls about two feet high and then arched to a half circle. The inports for flame should be vertical and open into the furnace at the top of the vertical wall; the outports for the gases of combustion should be vertical and at the same level as the inports and on the opposite side of the furnace from the inports. These outflues may be carried under the floor of the furnace to keep it hot.

The bottom of the door should be at the level of the ports to keep indraught air away from the steel. The annealing-pot is then the whole size of the furnace—two feet deep—and closed all around.

The draught should be regulated so that the flame will pass around the roof, or so nearly so as to never touch the steel, not even in momentary eddies.

In such a furnace clock-spring wire not more than .01 inch in diameter, or clock spring strands not more than .006 to .008 inch thick and several hundred feet long, may be annealed perfectly. The steel is scaled of course, but the operation is so quick and so complete that there is no decarbonized surface under the scale.

This plan is better than the Jones method or any closed method, because the big boxes necessary to hold the

strands or coils cannot be heated up without in some parts overheating the steel; all of which is avoided in the open furnace, because by means of peep-holes the operator can see what he is about, and after a little practice he can anneal large quantities of steel uniformly and efficiently.

VIII.

HARDENING AND TEMPERING.

For nearly all structural and machinery purposes steel is used in the condition in which it comes from the rolls or the forge; in exceptional cases it is annealed, and in some cases such as for wire in cables or for bearings in machinery, it is hardened and tempered.

For all uses for tools steel must be hardened, or hardened and tempered. The operations of hardening and tempering, including the necessary heating, are the most important, the most delicate, and the most difficult of all of the manipulations to which steel is subjected; these operations form an art in themselves where skill, care, good judgment, and experience are required to produce reliable and satisfactory results. It is a common idea that all that is necessary is to heat a piece of steel, quench it in water, brine, or some pet nostrum, and then warm it to a certain color; these are indeed the only operations that are necessary, but the way in which they are done are all-important.

An experienced steel-maker is often amazed at the confidence with which an ignorant person will put a valuable tool in the fire, rush the heat up to some bright color, or half a dozen colors at once, and souse it into the cooling-bath without regard to consequences. That such work

does not always result in disastrous fractures shows that steel does possess marvellous strength to resist even the worst disregard of rules and facts.

On the other hand, the beautiful work upon the most delicate and difficult shapes that is done by one skilled in the art cannot but excite the surprise and admiration of the onlooker who is familiar with the physics of steel, and who can appreciate the delicacy of handling required in the operation.

There are a few simple laws to observe and rules to follow which will lead to success; they will be stated in this chapter as clearly as may be, in the hope of giving the reader a good starting-point and a plain path to follow; but he who would become an expert can do so only by travelling the road carefully step by step. The hair-spring of a watch, or a little pinion or pivot, so small that it can only be seen through a magnifying-glass, the exquisitely engraved die costing hundreds or thousands of dollars, and the huge armor-plate weighing many tons, must all be hardened and tempered under precisely the same laws and in exactly the same way; the only difference is in the means of getting at it in each case.

Referring now to properties mentioned in the previous chapters, we have first to heat the piece to the right temperature and then to cool it in the quickest possible way in order to secure the greatest hardness and the best grain. In doing this we subject the steel to the greatest shocks or strains, and great care must be used.

The importance of uniformity in heating for forging and for annealing has been stated, and it has been shown how an error in this may be rectified by another and a more careful heating; when it comes to hardening, this uniformity

must be insisted upon and emphasized, for as a rule an error here has no remedy.

There may be cases of bad work that do not cause actual fracture that can be remedied by re-heating and hardening, but these are rare, because even if incurable fracture does not occur the error is not discovered until the piece has been put to work and its failure develops the errors of the temperer.

If the error is one of merely too low heat, not producing thorough hardening, it will generally be discovered by the operator, who will then try again and possibly succeed; but if the error be of uneven heat, or too much heat, the probabilities are that it will not be discovered until the piece fails in work, when it will be too late to apply any remedy.

Referring to Table I, Chap. V, treating of specific gravities, it is clear that all steel possesses different specific gravities, due to differences of temperature, and that these differences of specific gravity increase as the carbon content increases; it follows that if a piece of steel be heated unevenly, internal strains must be set up in the mass, and it is certain that if steel be quenched in this condition violent strains will be set up, even to the causing of fractures.

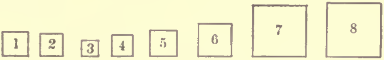
The theory of this action, as of all hardening, is involved in discussion which will be considered later; in this chapter the facts will be dealt with. When a piece of steel is heated, no matter how unevenly or to what temperature below actual granulation, and is allowed to cool slowly and without disturbance, it will not break or crack under the operation. If a piece be heated as unevenly as, say, medium orange in one part and medium lemon in another, and is then quenched, it will be almost certain to crack if it contains enough carbon to harden at all in the common

acceptance of the term, that is to say, file hard or having carbon 40 or higher.

This fact is too well known to be open to discussion; therefore the quenching of hot steel, the operation of hardening, does set up violent strains in steel, no matter what the true theory of hardening may be.

Referring to Chap. V, to the series of squares representing the apparent sizes of grain due to different temperatures, similar results follow from hardening, with the exceptions that the different structures are far more plainly marked, and the squares should be arranged a little differently; they are shown as continuously larger in Chap. V, from the grain of the cold bar up to the highest temperature; this is true if a bar has been rolled or hammered properly into a fine condition of grain. Of course if a bar be finished at, say, medium orange it will have a grain due to that heat—No. 3 in the series of squares. Then if it be heated to dark orange and cooled from that heat it will take on a grain corresponding to square No. 2, and No. 1 square will be eliminated.

The series of squares to represent hardened grain will be as follows:

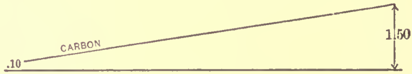


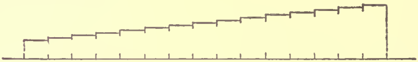
The heat colors being the same as before, viz.:

1. The natural bar—untreated.
2. Quenched at dark orange or orange red.
3. " " medium orange—*refined.*
4. " " bright orange.
5. " " dark lemon.
6. " " medium lemon.
7. " " bright lemon.
8. " " very bright lemon or creamy.

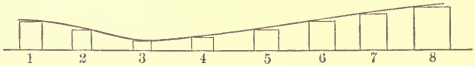
Heats 6, 7, 8 will almost invariably produce cracks although the pieces be evenly heated.

These squares do not represent absolute structures with marked divisions; they are only the steps on an incline, like the temper numbers in the carbon series; thus, the carbon-line is continuous, but the temper divisions repre-





sent steps up the incline. So with the series of squares, the changes of grain or structure are continuous, as represented by the doubly inclined line; the squares being



only the steps to indicate easily observed divisions. The minuteness of the changes is illustrated by the fact that in a piece heated continuously from creamy to dark orange and quenched, differences of grain have been observed unmistakably on opposite sides of pieces broken off not more than $\frac{1}{8}$ inch thick.

In practice the differences due to the colors given in the list above are as plain and surely marked as are the differences in the structure of ingots due to the different temper carbons already described.

In this hardened series each carbon temper gives its own peculiar grain; in low steel, say 40 carbon compared to

1.00 carbon or higher, No. 3 will be larger and No. 8 will be smaller in the low temper than in the high—another illustration of the fact that low steel is more inert to the action of heat than high steel. All grades and all tempers go through the same changes, but they are more marked in the high than in the low steel.

The grain of hardened steel is affected by the presence of silicon, phosphorus, and manganese, and doubtless by any other ingredients, these three being the most common.

It is in the grain of hardened steel that the conditions described in Chap. V as "sappy," "dry," and "fiery" are the most easily and frequently observed, although the same conditions obtain in unhardened steel in a manner that is useful to an observing steel-user. But it is in this hardened condition that the excellences or defects of steel are brought out and emphasized.

When a piece of steel is heated continuously from "creamy," or scintillating, down to black, or unheated, and is then quenched, the grain will be found to be coarsest, hardest, and most brittle at the hottest end, and with the brightest lustre, even to brilliancy, and to become finer down to a certain point, noted as No. 3 in the series of squares, or at a heat which shows about a medium orange color; here the grain becomes exceedingly fine, and here the steel is found to be the strongest and to be without lustre. Below this heat the grain appears coarser and the steel is less hard, until the grain and condition of the unheated part are reached. This fine condition, known as the *refined* condition, is very remarkable. It is the condition to be aimed at in all hardening operations, with one or two exceptions which will be noted, because in this state steel is at its best; it is strongest then, and it would seem to be clear without

argument that the finest grain and the strongest will hold the best at a fine cutting-edge, and will do the most work with the least wear, although a coarser grain may be a little harder, the coarser and more brittle condition of the latter more than counterbalancing its superior hardness.

The advantages of this refined condition are so great that it is found to be well to harden and refine mild-steel dies, and battering- and cutting-tools that are to be used for hot work, although the heat will draw out all of the temper in the first few minutes, because the superior strength of the fine grain will enable the tool to do twice to twenty times more work than an unhardened tool.

The refining-heat, like most other properties, varies with the carbon; the medium orange given is the proper heat for normal tool-steel of from about 90 to 110 carbon. Steel of 150 carbon will refine at about a dark orange, and steel of 50 to 60 carbon will require about a bright orange to refine it.

This range is small, but it must be observed and worked to if the best results are desired.

A color-blind person can never learn to harden steel properly.

In studying this phenomenon of refining, the conclusion was reached that it occurred at or immediately above the temperature that broke up the crystalline condition of cold steel and brought it fairly into the second, the plastic condition. Farther observation led to the conclusion that the coarser grain and greater hardness caused by higher heats were due to the gradual change from plastic toward granular condition that takes place as the heat increases. Later investigations have given no reason for changing these conclusions.

When the phenomenon of recalescence was observed and investigated by Osmond and others, different theories were advanced in explanation.

Langley concluded that if recalescence occurred at the change from a plastic to a crystalline condition, then the heat absorbed and again set free during such changes would account for the visible phenomenon of recalescence.

Again, if it should prove that recalescence occurred at the refining point, the conjunction of these phenomena would indicate strongly, first, that refining does occur at the point where this change of structure is complete in the reverse order, from crystalline to plastic; and second, the first being true, recalescence would be explained as stated, as indicating the inevitable absorption and emission of heat due to such a change.

Langley fitted up an electric apparatus for heating steel, in a box so placed that the light was practically uniform, that is, so that bright sunlight, or a cloudy sky, or passing clouds would not affect seriously the observation of heat-colors.

Pieces of steel were heated far above recalescence, up to bright lemon, and then allowed to cool slowly; in this way recalescence was shown clearly.

It was found to occur at the refining heat in every case, shifting for different carbons just as the refining heat shifts.

Immediately under the pieces being observed was a vessel of water into which the pieces could be dropped and quenched. After observing the heating and cooling until the eye was well trained, pieces were quenched at different heats and the results were noted. It was found that in the ascending heats no great hardness was produced until the

recalescence heat was reached or passed slightly; and in the descending heat excessive hardening occurred at a little below the recalescent heat, although no such hardening occurred at that color during ascending heats. This apparent anomaly is due simply to lag. If, in ascending, the piece be held for a few moments at the recalescent point, no increase being allowed, and then it be quenched, it will harden thoroughly and be refined. If, in descending, the cooling be arrested at a little below the recalescence for a few moments, neither increase nor decrease being allowed, and then the piece be quenched, it will not harden any better than if it be quenched immediately upon reaching the same heat in ascending.

Time must be allowed for the changes to take place, and lag must be provided for.

These experiments show that refining and recalescence take place at the same temperature.

AS TO HARDNESS.

Prof. J. W. Langley showed by sp. gr. determinations that steel quenched from 212° F. in water at 60° F. showed the hardening effect of such quenching, the difference of temperature being only 152° F.

Prof. S. P. Langley, of the Smithsonian, proved the same to be true by delicate electrical tests, and these again were confirmed by Prof. J. W. Langley in the laboratory of the Case School of Sciences.

A piece of refined steel will rarely be hard enough to scratch glass. A piece of steel quenched from creamy heat will almost always scratch glass. The maximum hardness is produced by the highest heat, or when temperature minus

cold is a maximum; the least hardness is found by quenching at the lowest heat above the cooling medium, or when temperature minus cold is a minimum—the time required to quench being a minimum in both cases.

What occurs between these limits? Is the curve of hardness a straight line, or an irregular line?

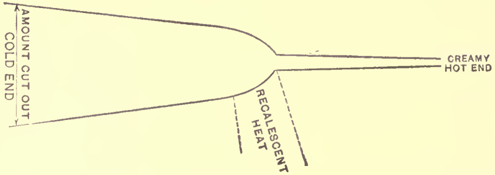
Let a piece of steel be heated as uniformly as possible from a creamy heat at one end to black at the other, and then be quenched.

Now take a newly broken hard file and draw its sharp corner gently and firmly over the piece, beginning at the black-heated end. The file will take hold, and as it is drawn along it will be felt that the piece becomes slightly harder as the file advances, until suddenly it will slip, and no amount of pressure will make it take hold above that point. The piece has become suddenly file hard.

Next try the same thing with a diamond; the diamond will cut easily until the point is reached where the file slipped, then there will be found a great increase of hardness.

From this point to the end of the piece it is observed readily by the action of the diamond that there is a gradual increase of hardness from the hump to the end of the piece to the creamy-heated end. Attempts were made to measure this curve of hardness by putting a load on the diamond and dragging it over the piece; but no diamond obtainable would bear a load heavy enough to produce a groove that could be measured accurately by micrometer. An examination of such a groove, through a strong magnifying-glass revealed the conditions plainly; the groove of

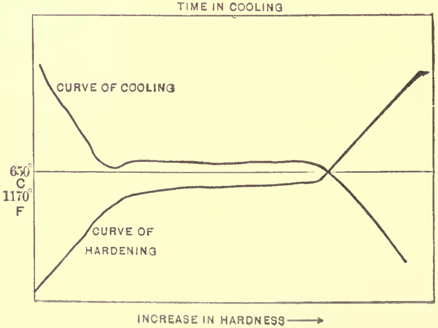
hardness may be illustrated on an exaggerated scale; thus:



The next question was, Where does this hump occur, and what is the cause of it?

Careful observation showed that it occurred at the point of recalescence, at the refining-point. This word point must not be taken as space without dimension in this connection; it is used in the common sense of at or adjacent to a given place. There is of course a small allowable range of temperature above any given exact point of recalescence, such as 655° C. or 1211° F.

By superimposing Langley's curves of cooling and of hardening (see Trans. Am. Soc. Civ. Eng., Vol. XXVII, p. 403), the relation between recalescence and the hardening-hump is obvious.



It is safe to say that experience proves that the *refined* condition is the best for all cutting-tools of every shape and form.

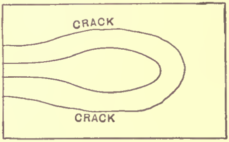
It seems to be obvious; the steel is then in its strongest condition, and when the grain is finest, the crystals the smallest, a fine edge should be the most enduring, because there is a more intimate contact between the particles. That a steel will refine well, and be strong in that condition is the steel-maker's final test of quality.

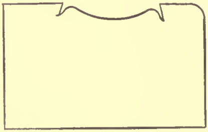
No steel-maker who has a proper regard for the character of his product will accept raw material upon mere analysis; analysis is of the utmost importance, for material for steel-making must be of a quality that will produce a certain quality of steel, or the result will be an inferior product. This applies to acid bessemer and open-hearth, and to crucible-steel especially; the basic processes admit of a reduction of phosphorus not obtainable in the others.

In making fine-tool steel a bad charge in the pot inevitably means a bad piece of steel. It may happen also that an iron of apparently good analysis will not produce a really fine steel; then there must be a search for unusual elements, such as copper, arsenic, antimony, etc., or for dirt, left in the iron by careless working. The refining-test then is as necessary as analysis, for if steel will not refine thoroughly it will not make good tools. Battering-tools, such as sledges, hammers, flatters, etc., should be refined carefully, for although their work is mainly compressive they are liable to receive, and do get, blows on the corners and edges that would ruin them if they were not in the strongest condition possible.

The reasons for refining hot-working tools have been stated already. Engraved dies for use in drop-presses

where they are subjected to heavy blows are undoubtedly in the most durable condition when they are refined, but they are subjected not only to impact, but to enormous compression, and therefore they must be hardened deeply. When a die-block is heated so as to refine, and then is quenched, it hardens perfectly on the surface and not very deeply, and it is quite common in such a case to see a die crushed by a few blows: the hardened part is driven bodily into the soft steel below it, and the die is ruined; thus:





To avoid this, such a die should be heated to No. 5, or a dark lemon, and quenched suddenly in a large volume of rushing water.

It will then have the enormous resistance to compression that is so well known in very hard steel, and it will be hardened so deeply that the blow of the hammer will not crush through the hard part. This is the best condition, too, of an armor-plate that is to resist the impact of a projectile.

It will be brittle, a light blow of a hammer will snip the corners, but it cannot be crushed by ordinary work. Dies made in this way have turned out thousands of gross of stamped pieces, showing no appreciable wear.

To harden a die in this way is a critical operation, because the strains are so enormous that a very trifling unevenness in the heat will break the piece, but the skill of expert temperers is so great that they will harden hun-

dreds of dies in this way and not lose one if the steel be sound.

HEATING FOR HARDENING.

A smith can heat an occasional piece for hardening, in his ordinary fire by using care and taking a little time. Where there are many pieces to be hardened, special furnaces should be used.

For thousands of little pieces, such as saw-teeth or little springs, a large furnace with a brick floor, and so arranged that the flame will not impinge on the pieces, is good.

The operator can watch the pieces, and as soon as any come to the right color he can draw them out, letting them drop into the quenching-tank, which should be right under the door or close at hand.

For twist-drills, reamers, etc., a lead bath, or a bath of melted salt and soda, is used. The lead bath is the best if care be taken to draw off the fumes so as not to poison the heaters. Because a bath of this kind is of exactly the right color at the top it is not to be assumed that pieces can be heated in it and hardened without further attention.

Thousands of tools are ruined, and thousands of dollars are thrown away annually, by unobserving men who assume that because a lead bath appears to be exactly the right color at the surface it is therefore just right.

A dark orange color surface may have underneath it an increasingly higher temperature, up to a bright lemon at the bottom, and tools heated in such a bath will have all of the varying temperatures of the bath; then cracked tools, twisted tools, brittle tools, tools too hard at one end and not hard enough at the other, will come out with exasperating regularity.

All of this can be avoided by a simple thorough stirring of the bath, to be done as often as may be necessary to keep it uniform.

In heating toothed tools, taps, reamers, milling-cutters, and the like, care should be taken that the points of the teeth never get above the refining-heat, the dark or medium orange required. It is no easy matter to do this except in a uniform bath, but it must be done. If the teeth are bright lemon, or even bright orange, when the body of the tool is at medium orange refining-heat, the probabilities are that they will shell off from the hardened tool as easily as the grains from a cob of corn.

Even if they are not so bad, if they do not crack off, they will be coarse-grained and brittle; they will not hold a good edge, and they will not do good work. If a long tool, such as a drill, etc., be heated medium orange on one side and bright orange on the other,—a difference of 100° to 200° F.,—and be quenched, it will come out of the bath curved; it must be curved. In quenching a long tool which it is desired to have straight it should be dipped vertically, so as to cool all around the axis simultaneously. If such a tool be dipped sideways, it will come out bent. In heating edge-tools of all kinds it is best to heat first the thicker part, away from the edge, and then when the body has come up to the refining-heat to draw the edge into the fire and let it come up last; as soon as a uniform color is reached quench promptly. If the edge be exposed to the fire in the beginning of the operation, it will almost certainly become too hot before the thicker parts are hot enough.

When a smooth, cylindrical piece is to be hardened, it should be rolled around from time to time while heating,

unless it is in a lead bath; if it be left to lie quietly in a furnace until it is hot, it will have a soft streak along the part that was uppermost.

The cause of this is not clear; the fact is as certain as hundreds of tests can make any fact. The experiment can be made by re-heating the piece with the soft streak down; then the original soft streak will come out hard, and another soft streak will be found on top. The changes can be rung upon this indefinitely.

A maker of roller-tube expanders had great trouble with his expander-pins; they cut, and wore out on one side. He tried many makes and many tempers of steel with the same result. He was told to turn his pins over and over as he heated them and his troubles would end. He replied: "Why, of course; I can see the reason and sense in that." If he did see the reason, he is the only person known, so far, who has done so. His pins worked all right from that time.

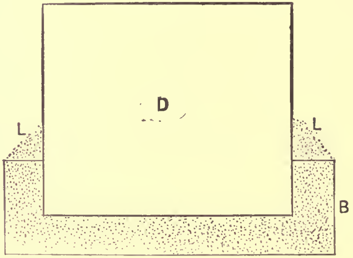
In hardening ROUND SECTIONS it is necessary to use great care to have the heat perfectly uniform and not too high, because the circular form is the most rigid, offering the greatest resistance to change. For this reason a round piece will be almost certain to split if it be heated above a medium orange, or if it be heated unevenly. Many a round piece is cracked by a heat, or by a little unevenness of heat, that another section would endure safely. A roll with journals is perhaps the most difficult of all tools to harden successfully; the most expert temperers will not be surprised at losing as many as one roll in five.

Engraved dies require to be hardened without oxidizing the engraved face, so that the finest lines will be preserved clear and clean.

This is done by burying the engraved face in carbonaceous material in such a way as to prevent the flame or any hot air from coming in contact with it.

There are many ways of doing this, and many different carbonaceous mixtures are used ; one simple, and known to be satisfactory, plan will be explained as sufficient to give any intending operator a good starting-point.

The carbonaceous material preferred is burnt leather powdered—and the older it is the better—until it is reduced to ash, so that the material should be saved after each operation to be used again mixed with enough new material to make up the necessary quantity.



D is the die to be heated ; *B* is an open box about two inches deep and one inch larger each way than the die; *L* is the burnt leather packed in thoroughly, and as full as the box will hold. The engraved face is down, embedded in the burnt leather, and secure from contact with flame or air.

Sometimes powdered charcoal is used, with or without a mixture of tar, according to the fancy of the operator.

Some operators prefer to have the box so high as to

leave only the top surface of the embedded die exposed, but the most successful workers prefer the plan sketched, because they can see more of the die, and so regulate better the even heating.

The die and box are put in the furnace, and the heating is watched, the die being turned and moved about in the furnace so as to obtain a perfectly even heat.

When the right temperature is reached, the whole is withdrawn from the furnace; the die is lifted out of the box and plunged into the water immediately. There must be no delay at this point whatever; a few moments' exposure of the hot die to the air will result in oxidation and scaling of the engraving.

In heating such a die a furnace should be used. It can be done in a smith's fire, but it is a hazardous plan, and gives many chances for a failure.

A furnace with an even bed of incandescent coke is good, and such a furnace is very useful for many other purposes.

Where many dies are to be hardened, the handiest appliance is a little furnace with brick floor and lining, and heated by petroleum or gas, so arranged that the flames will not impinge upon the piece to be heated.

Such furnaces are now made to work so perfectly that illuminating-gas is found to be an economical fuel.

For quenching there should be plenty of water. For small dies that can be handled easily by one man a large tub or tank of water will answer if the operator will keep the die in rapid motion in the water.

Running water is the best. A handy plan is to have the inlet-pipe project vertically a short distance through the bottom of the tank, producing a strong upward current

which will strike directly against the face of the submerged die.

Some prefer a downward stream; others a side stream; others, again, prefer a shower-bath; and, again, some use side jets.

A very efficient tank has a partition running from a few inches from the bottom to within a few inches of the surface of the water, and so placed as to separate, say, nine tenths of the tank from one tenth. In the smaller compartment there is an Archimedean screw driven at a speed of 200 to 300 revolutions; this drives the water under the partition and out over the top in a violent current. The steel is quenched in the larger space. Where water is an item of expense, this plan is economical, and it is certainly efficient.

An excellent way of quenching large faces, such as anvils, is to have a tank raised twelve to fifteen feet from the floor. In the bottom of the tank is a pipe with a valve, to be operated by a lever. The whole is enclosed in a sort of closet with a door in one side. When the piece is hot, it is placed immediately under the pipe, the door is closed, the valve is opened, and a great body of water is dashed down upon the face that is to be hardened.

A slight modification of this plan is used in hardening armor-plates, where many jets are used to insure even quenching of the large surface. This plan is supposed to be patented, or, more properly, it is patented; but as it is very old and well known the patent should not be allowed to disturb anybody.

Water only has been mentioned so far as a quenching medium, because it is the simplest and the cheapest generally. Oil is used frequently where extreme hardness is

not necessary and toughness is desirable. Oil gives a good hardness with toughness, and it is used almost universally for springs, and it is sometimes used to toughen railroad axles and similar work. The oil acts more slowly than water and leaves the piece in more nearly a tempered condition; it is neither so hard nor so brittle as it would be if quenched in water. Straits fish-oil is good and cheap; lard-oil gives greater hardness than fish-oil; mineral oil is too fiery to use safely; but there are mixed oils in the market made expressly for hardening which are cheap and efficient.

If it is desired to get the greatest hardness, brine will harden harder than fresh water; and mercury will give the greatest hardness of all. It is a rather expensive cooling medium.

Acid added to water increases its hardening power; but those who know the effects of acids will be very chary of using them.

As to heating, too much emphasis cannot be given to the importance of even temperature throughout the mass. The illustration of the painted piece mentioned in connection with heating for forging applies more forcibly here. Every piece that is to be quenched should look as if it were covered with a perfectly even coat of paint of the exact tint necessary to give the best result.

All hardening should be done on a rising temperature, because then the grain and strains cannot be greater than those due to the highest heat, and this maximum heat can be watched and kept within limits. If a piece be quenched from a falling temperature, the grain and strains will be those due to the highest temperature, modified slightly by the distance through which it has cooled, and always coarser

and more brittle than if quenched at the same heat produced by rising temperature. If by accident a piece gets too hot to be quenched, it should be allowed to go entirely cold, and then be heated again to the right color.

After a piece of steel is hardened it is usually tempered to relieve some of the strain, reduce brittleness, and increase the toughness.

This is done by heating; usually the piece is held over the fire, or in contact with a large piece of steel or iron heated for the purpose, until it takes on a certain color which indicates the degree of tempering that is wanted.

Where great numbers of pieces are to be tempered, a bath is very convenient. Boiling in water produces only a slight tempering sufficient for some purposes. Steaming under given pressure will produce even heating and uniform tempering.

When pieces are quenched in oil, they can be tempered easily and nicely by watching the oil that adheres to them. When the oil is dried off and begins to char, the tempering is good, about right for saw-teeth. If the heat is run up until the oil flashes, the tempering is pretty thorough and is about right for good springs. If the oil be all burned off, there will be little temper left except in very high steel. High steel becomes much harder when quenched than low steel; consequently very high hardened steel may be heated until it begins to show color and still retain considerable hardness or temper, whereas a milder steel, under 90 or 100 carbon, when heated to such a degree will retain no temper, it will be soft.

Saw-teeth, tap, reamer, and milling-cutter teeth, may be drawn, and usually should be drawn, down until a file will barely catch them; then they will do excellent work. Many

inexperienced temperers are apt to complain if such tools can be filed at all when drawn to the proper color, forgetful or ignorant of the fact that a file should always contain about twice as much carbon as a tap or reamer, and that if both are drawn to the same color the file must necessarily be the harder. Such men often destroy much good work by trying to get the tools too hard. If a tap-tooth be left file hard, it will be pretty certain to snip off when put to work.

TEMPER COLORS.

When a clean piece of iron or steel, hardened or unhardened, is exposed to heat in the air, it will assume different colors as the heat increases. First will be noticed a light, delicate straw color; then in order a deep straw, light brown; darker brown; brown shaded with purple, known as pigeon-wing; as the brown dies out a light bluish cast; light brilliant blue; dark blue; black.

When black, the temper is gone. It is well established that these colors are due to thin films of oxide that are formed as the heat progresses.

These colors are very beautiful, and as useful as they are beautiful, furnishing an unvarying guide to the condition of hardened steel.

The drawing of hardened steel to any of these colors is *tempering.*

So we have the different tempers:

Light straw........	For lathe-tools, files, etc.
Straw	" " " " "
Light brown.......	" taps, reamers, drills, etc.
Darker brown......	" " " " "
Pigeon-wing.......	" axes, hatchets, and some drills
Light blue........	" springs
Dark blue.........	" some springs; but seldom used

This is the unfortunate second use of the word temper, which must be borne in mind if confusion is to be avoided in consulting with steel-makers and steel-workers. The meanings may be tabulated thus :

Temper.	Steel-maker's Meaning.	Steel-worker's Meaning.
Very high............	150 carbon +	light straw
High	100 to 120 C	straw
Medium..............	70 to 80 C	brown to pigeon-wing
Mild.................	40 to 60 C	light blue
Low.................	20 to 30 C	dark blue
Soft or dead soft......	under 20 C	black

The uses given for temper colors are not meant to be absolute; they merely give a good general idea; experienced men are guided by results, and temper in every case in the way that proves to be most satisfactory.

DIFFERENCE BETWEEN CRACKS AND SEAMS.

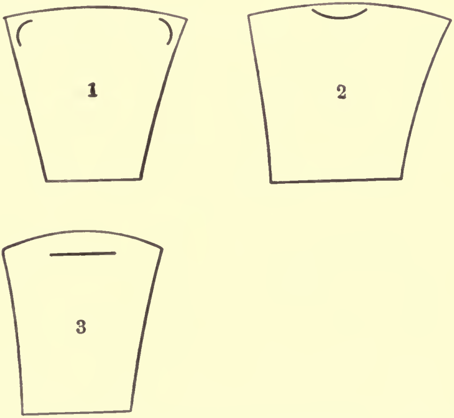
When temperers find that their tools are cracking under their treatment, they are apt to assume that, as they are working in their ordinary way, there must be something wrong with the steel. It is either seamy, or harder than usual, or not uniform in temper, or it is of inferior quality.

All or any of these conditions may exist and be the cause of the trouble; but every man should bear in mind that he is also a variable quantity; he may be unwell and not see and observe as closely as usual; there may be a long spell of unusual weather giving him a light differing from that to which he is accustomed; or, as is often the case, he may simply have unconsciously departed from the even track by not having his mind carefully intent upon the routine which has become a sort of second nature to him, so that for a time he ceases to think, makes of himself an

animated machine, and the machine left to itself does not run with perfect regularity.

If personal pride, egotism, or ill temper be set aside, it is always easy to find out whether the fault is in the steel or in the man; that once determined the remedy is easily applied, and the sooner the better for all parties.

How to Break a Tool. Let an ordinary axe be considered.



If the axe be cracked as shown in Fig. 1, the corners have been hotter than the middle of the blade; probably by snipping the corners and the middle and comparing the fractures the coarser grain at the corners will tell the tale.

If the crack be as shown in No. 2, the middle of the blade has been hotter than the corners; snipping and comparing the grains will tell the story.

If the crack be more nearly a straight line, as shown in number 3, the chances are that there is a seam there and the steel is at fault.

How to Tell a Seam from a Water-crack.—A seam is caused by a gas-bubble in the ingot which has not been closed up by hammering or rolling; it always runs in the direction of the work; in bars it is parallel to the axis.

The walls of a seam are always more or less smooth, the surfaces having been rubbed together under heavy pressure during hammering or rolling, and they are black usually, being coated with oxide.

The walls of a water-crack are never smooth, they are rough and gritty, and they may have any of the temper colors caused by the action of water and heat.

There need never be any question as to which is which.

If a long tool cracks down the middle, it may be from too much heat, from seams, or from a lap.

A lap is caused by careless working under a hammer, or by bad draughts in the rolls, folding part of the steel over on itself. Laps, like seams, run parallel to the axis of a bar, and usually in very straight lines.

Any long piece of steel may be split in hardening by too much heat. In making the experiment of heating a piece continuously from scintillating, or creamy color, down to black, to show the differences of grain due to the different heats, the sample almost invariably splits down the middle as far as the strong, refined grain, or nearly that far.

As stated before, a round bar will be almost certain to split if it be heated up to medium lemon, although a square bar may endure the same heat without cracking.

An examination of the walls of a split will settle at once whether it is a seam, a lap, or a water-crack.

A seam will not necessarily be long; its walls will be smooth.

A lap usually runs the who'e length of the bar, and the walls are smooth.

By smooth walls of seams and laps comparative smoothness is meant; they are sometimes polished, but not always, and they are never granular like the walls of water-cracks.

If the split be a water-crack, the walls will be rough and granular.

After a temperer has straightened himself out, and brought his work to usual accuracy and uniformity, if his tools continue to crack and indicate weakness in the steel, it is time for him to suspect the character of his material and to require the steel-maker to either show up the faults in tempering, or improve the quality of his product.

A WORD FOR THE WORKMAN.

Give him a chance. A steel-worker to be expert must have a well-trained eye and know how to use it. He must work with delicate tints, ranging in the yellows from creamy yellow to dark orange or orange red as extremes, and most of his work must be done between bright lemon and medium orange in forging, and between rather dark to medium orange, or possibly nearly light orange, when hardening and tempering.

Probably in no other business is there such ridiculous waste as is often found in steel-working where the manufacturer economizes in his blacksmiths.

A large, wealthy railroad condemns a brand of steel. The steel-maker goes to the shop and is informed by a bright, intelligent blacksmith that the steel will not make a track-

chisel. It is a hot summer day; the smith is working over a huge fire with a large piece of work in the middle of the fire and a number of small pieces of steel stuck in the edge of the fire.

He is welding large iron frog-points, and in the interval he is filling a hurried order for four dozen track-chisels for which the trackmen are waiting. He is not merely forging the chisels, he is hardening and tempering them. The glare of the welding-work makes him color-blind, the hurry gives him no time for manipulation, and the trackmen have no chisels.

After a thorough expression of sympathy for the smith the steel-maker turns upon the foreman and master mechanic, and gives them such a tongue-lashing that they turn away silenced and ashamed.

Page after page of such cases could be written, but one should be enough.

A steel-maker has a thoroughly skilled and expert steel-worker; he rushes into the shop and says, "Mike, refine this right away, please; I want to know what it is."

Mike replies, "I will do that to-morrow; I am welding to-day."

That is entirely satisfactory; those men understand one another, and they know a little something about their business.

A temperer should do no other work when he is heating for hardening, and he should always be allowed to use as much time about it as he pleases, assuming that he is a decently honest man who prefers good work to bad; and as a rule such honest men are in the majority, if they are given a fair chance.

IX.

ON THE SURFACE.

THE condition of the surface of steel has much to do with its successful hardening and working.

A slight film adherent to the surface of steel will prevent its hardening properly; the steel may harden under such a film and not be hard upon the immediate surface, and, as in almost every case a hard, strong surface is necessary to good work, it is important that a piece of steel to harden well should have a clean surface of sound steel.

It has been stated already that all bars and forgings of steel have upon the surface a coat of oxide of iron, and immediately beneath this a thin film of decarbonized iron.

Neither of these substances will harden, and in every case where a hard-bearing surface or a keen-cutting edge is desired these coatings must be removed. Polished drill-wire and cold-rolled spring-steel for watches, clocks, etc., should have perfect surfaces, and it is the duty of steel-makers to turn them out in that condition. All black steel, or hot-finished steel, contains these coatings.

In the manufacture of railroad, wagon, and carriage springs it is not necessary or customary to pay any attention to these coatings; the body of the steel hardens well, giving the required resilience and elasticity, so that an un-

hardened coat of .01 to .001 inch thick does no harm. To all bearing-surfaces and cutting-edges such coatings are fatal.

The ordinary way of preparing steel is to cut the skin off, and this is sufficient if enough be take off; it happens often that a purchaser, in pursuit of economy and unaware of the importance of this skin, orders his bars or forgings so close to size that when they are finished the decarbonized skin is not all removed, and the result is an expensive tap, reamer, milling-cutter, or some tool of that sort with the points of the teeth soft and worthless.

In small tools $\frac{1}{16}$ inch, in medium-size tools, say up to two or three inches in diameter, $\frac{1}{8}$ inch cut off should be plenty; in large tools and dies, especially in shaped forgings, it would be wiser to cut away $\frac{3}{16}$ inch.

In many cases sufficient hardness can be obtained by pickling off the surface-scale, but this will not do where thorough hardening is required, because the acid does not remove the thin decarbonized surface. It seems to be impracticable to remove the decarbonized skin by the action of acid, for if the steel be left in the acid long enough to accomplish this the acid will penetrate deeper, oxidizing and ruining the steel as it advances.

Grinding is frequently resorted to, being quicker and cheaper than turning, planing, or milling.

When grinding is used, care must be taken not to glaze the surface of the steel, or if it should be glazed the glaze must be removed by filing or scraping.

In the manufacture of files it is customary to grind the blanks after they are forged and before the teeth are cut.

After the blanks are ground they are held up to the light and examined carefully for glaze. Every blank that

shows by the flash of light that it is glazed is put to one side; then these glazed blanks are taken by other operatives and filed until all traces of glaze are removed. The file-maker will explain that if this be not done the files when hardened will be soft at the tips of the teeth over the whole of the glazed surface. This inspection and filing of blanks involves considerable expense, and it is certain that such an expense would not be incurred if it were not necessary.

This glaze does not appear to be due to burning, at least the stones are run in water; the blanks are handled by the bare hands of the grinders, and do not appear to be hot.

After pieces are hardened and tempered they frequently require grinding to bring them to exact dimensions. This is usually done on emery-wheels with an abundance of water, and as no temper colors are developed indicating heat it is assumed that no harm can be done.

Just here much valuable work is destroyed. The tempered piece is put on the wheel, in a "flood of water"; the work is rushed, and the piece comes out literally covered with little surface-cracks running in every direction, perfectly visible to the naked eye. Until the steel-worker learns better he blames and condemns the steel.

This result is very common in the manufacture of shear-knives, scissors, shear-blades, dies, etc.

Sometimes too a round bearing or expander-pin is hardened; examined by means of a file it appears perfectly hard; it is then ground, not quite heavily enough to produce surface-cracks, but still heavily, and on a glazed wheel. It is found now that the surface is soft; only a thousandth of an inch or so has been cut off, and the steel is condemned at once because it will harden only skin deep.

Let the file be drawn heavily over the surface and it will be found that the soft surface is only about a thousandth of an inch thick, and underneath the steel is perfectly hard.

Now grind slightly on a sharp, clean wheel and re-harden; the surface will be found to be perfectly hard. Ground heavily again on the glazed wheel, it will become soft, as before. These operations can be repeated with unvarying results until the whole piece is ground away.

These difficulties occur more with emery-wheels than with grindstones, either because emery-wheels glaze more easily than grindstones, or because, owing to their superior cutting powers under any circumstances, they are more neglected than grindstones.

Experience shows that these bad results occur almost invariably on glazed wheels. It is rare to find any bad work come off from a clean, sharp wheel, unless the pressure has been so excessive as to show that the operator is either foolish or stupid.

The remedy is simple: Keep the wheels *clean* and *sharp.*

Many grinders who understand this matter will not run any wheel more than one day without dressing, nor even a whole day if the work is continuous and they have reason to apprehend danger.

A FEW WORDS IN REGARD TO PICKLING.

Pickling is the placing of steel in a bath of dilute acid to remove the scale. It is a necessary operation in wire-making and for many other purposes, and it may be hastened by having the acid hot.

Sulphuric acid is used generally; it is efficient and cheap. When thin sheets are to be pickled, the acid should not be

too hot, or it will raise a rash all over the sheet in many cases. This indicates some unsoundness in the steel, the presence probably of innumerable little bubbles of occluded gases. This is possibly true, yet the same sheets pickled properly and brought out smooth will polish perfectly, or if cut up will make thousands of little tools that will show no evidence of unsoundness.

Steel should never be left in the pickling-bath any longer than is necessary to remove the scale; it seems unnecessary to warn readers that the acid will continue to act on the steel, eat the steel after the scale is removed. When taken from the pickle, the steel should be washed in limewater and plenty of clean running water; but this does not take out all of the acid. It should then be baked for several hours at a heat of 400° to 450° F. to decompose the remaining acid. This is just below a bluing heat, and it does not discolor or oxidize the surface. It is known as the sizzling-heat, the heat that the expert laundry-woman gets on her flat-iron which she tests with her moistened finger.

Acid if not taken off completely will continue to act upon and rot the steel: how far this will go on is not known exactly; for instance, it is not known whether if a block six inches cube were pickled and merely washed, the remaining acid would penetrate and rot the whole mass or not. There must be some relation between the mass of the steel and the power of a small amount of acid to penetrate.

The power of acid can be illustrated on the other extreme: A lot of watch-spring steel is finished in long coils and .010 inch thick; when last pickled, the baking was neglected; the steel is tough, it hardens well, and

when tempered it is springy and strong; by all of the tests it is just right in every coil. It is shipped away and in three or four weeks the spring-maker begins work on it. He reports at once that it is rotten and worthless, it will not make a spring at all, and he is angry. The steel is returned to the maker and he finds the report true: the steel is rotten and worthless. Then by diligent inquiry he finds that the last baking was omitted, and he pockets his loss, sending an humble apology to the irate spring-maker.

Whether the residual acid can ruin a large piece of steel or not need not be considered when the simple operation of baking will remove the possibility of harm.

X.

IMPURITIES IN STEEL.

ANY elements in steel which reduce its strength or durability in any way may be classed as impurities.

A theoretical ideal of pure steel is a compound of iron and carbon; it is an ideal that is never reached in practice, but it is one that is aimed at by many manufacturers and consumers, because experience shows that, especially in high steels, the more nearly it is attained the more reliable and safe is the product.

All steel contains silicon, phosphorus, sulphur, oxygen, hydrogen, and nitrogen, none of which add any useful property to the material. It is admitted that, starting with very small quantities of silicon or phosphorus in mild steel, small additions of either element will increase the tensile strength of the steel perceptibly up to a given amount, and that then the addition of more of either one will cause a reduction of strength. The same increase of strength can be obtained by the addition of a little carbon, producing a much more reliable material. It is not known that even such slight apparent gain in strength can be made by using oxygen, nitrogen, or hydrogen.

Manganese is present in all steel as a necessary ingredient, it gives an increase in strength in the same way as phosphorus, and when increased beyond a small limit it causes brittleness. Hadfield's manganese steel is a unique

material, not to be considered in connection with the ordinary steel of commerce.

Webster's experiments are perhaps the most complete of any that show the effects of small increases of silicon, phosphorus, sulphur, and manganese, but as these are not completed they are not quoted here, because Mr. Webster may reach additional and different results before these pages are printed.

The chief bad qualities of steel that are caused by these impurities are known as "red-shortness," "cold-shortness," and "hot-shortness."

A steel is called red-short when it is brittle and friable at what is known commonly as a low red heat—"cherry red," "orange red."

Red-shortness is caused chiefly by sulphur or by oxygen; many other elements may produce the same effects; it seems probable that nitrogen may be one of these, but the real action of nitrogen is as yet obscure.

A red-short steel is difficult to work; it must be worked at a high heat—from bright orange up to near the heat of granulation—or it will crack. When hardened, it is almost certain to crack. When red-short steel is worked with care into a sound condition, it may when cold be reasonably strong, but hardly any engineer of experience would be willing to trust it.

Hot-short steel is that which cannot be worked at a high heat, say above a medium to light orange, but which is generally malleable and works soundly at medium orange down to dark orange, or almost black.

This is a characteristic of most of the so-called alloy steels, or steels containing considerable quantities of tungsten, manganese, or silicon. It is claimed that chrome

steel may be worked at high heats and that it is less easily injured in the fire than carbon steel. This is not within the author's experience. It is this property of hot-shortness that makes the alloy steels so expensive; the ingots cannot be heated hot enough nor worked heavily enough to close up porosities, and therefore, there is a heavy loss from seams.

The range of heat at which they can be worked is so small that many re-heatings are required, increasing greatly the cost of working.

As compared to good carbon steel they are liable to crack in hardening, and when hardened they are friable, although they may be excessively hard.

Cold-short steel is steel which is weak and brittle when cold, either hardened or unhardened. Of those which are always found in steel, phosphorus is the one well-known element which produces cold-shortness.

It is clear that no one can have any use for cold-short steel.

Red-short or hot short steel may be of some use when worked successfully into a cold condition, but cold-short steel is to be avoided in all cases where the steel is used ultimately cold.

If the theoretically perfect steel is a compound of iron and carbon, it cannot be obtained in practice, and the only safeguard is to fix a maximum above which other elements are not to be tolerated.

In tool-steel of ordinary standard excellence such maximum should be .02 of one per cent; it may be worked to easily and economically, except perhaps in silicon, which element is generally given off to some extent by the crucible; it should be kept as low as possible, however, say well

under 10, one tenth of one per cent. Some people claim that a little higher silicon makes steel sounder and better; but any expert temperer will soon observe the difference between steels of .10 and .01 silicon. For the highest and best grade of tool-steel the maximum should be the least attainable. Every one hundredth of one per cent of phosphorus, silicon, or sulphur will show itself in fine tool-steel when it is hardened. It is assumed, of course, that such impurities as copper, antimony, arsenic, etc., exist only as mere traces, or not at all.

As oxygen must be at a minimum, no one has yet succeeded in making a really fine tool-steel from the products of the Bessemer or of the open-hearth process.

The removal of the last fractions of these impurities is difficult and expensive; for instance, a steel melting iron of

Silicon	.03 to .06
Phosphorus	.03 " .02
Sulphur	.002 or less

may be bought for 2 cents a pound or less, whereas an iron of

Silicon	$<$ .02
Phosphorus	$<$ .01
Sulphur	trace

can hardly be bought for less than 5 cents a pound.

This difference of three cents a pound is justifiable when the highest grade of tool-steel is to be made; and it would be silly to require any such material in any spring, machinery, or structural steel.

In addition to these impurities there are other difficulties to be guarded against, chief among which is an uneven distribution of elements.

In all steel there is some *segregation;* that is to say, as the liquid metal freezes, the elements are to some extent squeezed out and collected in that part of the ingot which congeals last. It is claimed that in the Bessemer and Open-hearth processes any ferro-silicon added to quiet a heat, or any ferro-manganese added to remove oxygen, are at once absorbed and distributed through the mass, and so when any serious irregularity is discovered it is charged to *segregation.*

A heat may produce billets of 75 carbon and 120 carbon, and again it is called segregation.

As a rule, inertia has more to do with such differences than segregation. One crucible of steel may produce an ingot containing 90 carbon and 130 carbon. Segregation has nothing to do with this: a careless mixer has put a heavy lump of 140- or 150-carbon steel in the bottom of the pot and covered it up with iron. The steel melted first and settled in the bottom of the pot, the iron melted later and settled on top of the steel, and they did not mix. The teeming was not sufficient to cause a thorough mixing.

Segregation covers a multitude of sins.

Exactly how much is sin and how much is segregation will not be known until analyses are made of the top, middle, and bottom of the bath, and of the contents of the ladle, these to be compared to analyses of the top, bottom, and middle of the ingots. There is certainly an unavoidable amount of segregration, and as equally certain an amount of curable irregularity due to inertia.

WILD HEATS.

After steel is melted, whether in a crucible, an open hearth, or a Bessemer vessel, it boils with more or less violence. This boiling is caused by ebullition of gases, and if steel be poured into moulds while it is boiling the resulting ingot will be found to be honeycombed to an extent that is governed by the degree of the boiling.

If a heat boils violently and persistently, it is said to be "wild," and if a wild heat be teemed the ingots will be honeycombed completely; such ingots cannot be worked into thoroughly sound steel, and no melter who has any regard for his work will teem a wild heat if he knows it.

To stop the boiling is called "dead-melting," "killing" the steel, so that it shall be quiet in the furnace and in the moulds.

A crucible-steel maker who knows his business can, and he will, always dead-melt his steel. It only requires a few minutes of application of a heat a little above melting temperature, and this can be applied by a skilled melter without burning his crucible or cutting down his furnace; this is indeed about all of the art there is in crucible-melting, the remaining operations being easy and simple.

Dead-melting in the Bessemer vessel is not possible by increase of time; wild heats are managed differently, probably by adding manganese or silicon, or both, but exactly how is not within the author's experience.

Dead-melting in the open hearth would appear at first sight to be always possible, but there are more difficulties in the way than in the case of crucible-melting.

The heat may be wild when the right carbon is reached,

and then the melter must use a little ferro-silicon, or silico-spiegel, or highly silicious pig, or aluminum, and he must use good judgment so as not to have his steel overdosed with any of these. From half an ounce to an ounce of aluminum to a ton of steel is usually sufficient, and although any considerable content of aluminum is injurious to steel there is little danger of its being added, because of its cost, and because a little too much aluminum will cause the ingots to pipe from top to bottom.

Silicon seems to be the most kindly element to use, and it is claimed that a content of silicon as high as 20 is not injurious; some people claim that it is beneficial. That it does help materially in the production of sound steel there can be no doubt, and if such steel meets all of the requirements of the engineer and of practice it would seem to be wise not to place the upper limit for silicon so low as to prevent its sufficient use in securing soundness. But the author cannot concede that as much as 20 silicon is necessary. In crucible practice high silicon is not necessary; in "melting-iron," or iron to be melted, it means so much dirt, indicating careless workmanship; but there will always be a little silicon present which the steel has absorbed from the walls of the crucible during the operation of melting. In high tool-steel silicon should be at the lowest minimum that is attainable.

This discussion of wild heats may appear to be outside of the scope of this work, and to belong exclusively to the art of manufacturing steel, of which this book does not pretend to treat. This is true so far that it is not recommended that the engineer shall meddle in any way with the manufacturer in the management of his work; on the other hand, it is vital to the engineer that he should know

about it, because wild steel may hammer or roll perfectly well, it may appear to be sound, but the author cannot believe that it is ever sound and reliable.

Again, it has a scientific interest; that wildness is due to too much gas, and probably to carbon-gas, may be shown by an illustration.

It has its parallel in the rising of the iron in a puddling-furnace at the close of the boil, a phenomenon with which every one is familiar who has watched a heat being boiled or puddled. That all of the iron does not run out of the puddling-furnace at this stage is owing to the fact that there is not heat enough in the puddling-furnace to keep the iron liquid after it has been decarbonized.

During the running of a basic open-hearth furnace an apparently dead heat was tapped; before the steel reached the ladle there was a sort of explosion; the steel was blown all over the shop, the men had to run for their lives, and not one tenth of the steel reached the ladle. The manager was rated roundly for carelessness in not having dried his spout, and the incident closed. A few days later another quiet heat was tapped and it ran into the ladle; about the time the ladle was full the steel rose rapidly, like a beaten egg or whipped cream, and ran out on to the floor, cutting the sides of the ladle, the ladle-chains, and the crane-beams as it flowed. The men ran, and there was no injury to the person.

Again the manager was blamed, this time for having a damp ladle, and he was notified of an impending dismissal if such a thing occurred again. He protested that he knew the ladle and the stopper were red-hot, that he had examined them personally and carefully, and knew he stated the truth.

There were several reasons for looking into the matter farther: first, the man in charge was known to be truthful and careful, so that there was no reason for doubting his word; second, if the vessel and rod were red-hot, there could be no aqueous moisture there ; and, finally, such an ebullition from dampness was contrary to experience, as a small quantity of water *under* a mass of molten iron, or slag, results almost invariably in a violent explosion, like that of gunpowder or dynamite.

Upon inquiry it was found that prior to both ebullitions there had been a large hole in the furnace-bottom, requiring about a peck of material to fill it in each case. Magnesite was used; the magnesite was bought raw, and burned in the place. It is well known that it takes a long time and high heat to drive carbonic acid out of magnesite, and it was surmised that insufficient roasting might have caused the trouble. Samples of burned and of raw magnesite were sent to the laboratory, and the burned was found to contain about as much carbonic acid as the raw magnesite. Then the case seemed clear: This heavily charged magnesite was packed into the hole; the heat was charged and melted. The magnesite held the carbonic acid until near the close of the operation; then the intense heat of the steel forced the release of the gas, which was at once absorbed by the steel. Owing to the superincumbent weight of the steel the gas was absorbed quietly, and when the weight was removed the gas escaped, exactly as it does at the close of puddling or in the frothing of yeast.

Whether the carbonic acid remained such, or whether it took up an equivalent of carbon and became carbonic oxide, and then again took up oxygen from the bath, and so kept on increasing in volume, is not known

The facts seem clear, and the collateral proof is that thorough burning of the magnesite, and of any dolomite that was used, prevented a recurrence of any such accidents.

Such ebullitions have occurred and caused the burning to death of pitmen, and the statement of the above case may be of use to melters in the future who have not met such an experience.

OXYGEN AND NITROGEN.

Oxygen and nitrogen are present in all steel and both are injurious, probably the most so of all impurities.

The oxides of iron are too well known to need discussion or description; they are the iron ores mixed with gangue. They are brittle, friable, hard, and weak, like sandstones. Mixed in steel they can be nothing but weakeners, elements of disintegration. Let any one take a handful of scale—or rust—oxide of iron, in his fingers and crumble it, and it will be difficult for him to imagine how such material could be anything but harmful when incorporated in steel. Langley has shown, and other scientists have confirmed him, that oxygen may exist in iron in solution, and not as oxide: the discovery was attended with the assertion that such dissolved oxygen produced excessive red-shortness. The proof that red-shortness was caused in this way was completed by the removal of the oxygen from some extremely red-short steel; the red-shortness disappeared with the oxygen and the steel worked perfectly.

When steel is melted very low in carbon, by any process, it is certain to be red-short and rotten unless the greatest care be used to prevent the introduction of oxygen.

Crucible-steel of 15 carbon or less will as a rule be red-short and cold-short; it will not weld, and is generally thoroughly worthless. The same material melted to contain 18 to 25 carbon will be tough and waxlike, hot or cold. It will weld easily into tubes, and may be stamped cold into almost any desired shape.

Bessemer or open-hearth steel of less than 8 carbon is almost certain to be equally worthless, whereas the same material blown or melted not below 10 or 12 carbon, and re-carbonized not above 20, will be tough and good at any heat under granulation, and equally good and tough when cold.

As to Bessemer steel, the author cannot say whether it would be possible to stop the blow between 10 and 15 carbon or not, but it seems certain that if there be no overblowing red-shortness and cold-shortness may be avoided by carbonizing back to about 15 by the use of manganese or silicon, or both together.

In the open hearth it is always possible to stop the melt at 10 carbon, and to deoxidize the heat so as to avoid shortness, and not to go above 20 carbon. Such steel will be sound and tough; it will weld and stamp perfectly, and will be satisfactory for all reasonable requirements.

The reason of this seems to be simple and plain: In melting or blowing out the last fractions of carbon below 10 to 15 the same quantity of air per second or minute must be used as when burning out the higher quantities, and now there is so little carbon to be attacked that the oxygen necessarily attacks the iron in greater and greater force as the carbon decreases.

This leaves an excess of oxygen in the steel which cannot

be removed by the ordinary quantities of silicon, or manganese, or aluminum.

If more manganese or silicon be used, the red-shortness and weakness can be cured largely; but then the carbon is raised considerably, and thus the steel is brought up to where it would have been without this excessive decarbonizing, with the difference that it is not quite so strong.

What good is there, then, in extremely low melting?

It must be admitted that there are tough, good-working steels in the market of carbon < 5, manganese < 20. They are made in small furnaces, worked with great care; the product is expensive, and, unless it is wanted to be welded in place of common wrought iron, it is in no case as good as well-made steel of 12 to 20 carbon; even for welding the latter is superior if the worker will only be satisfied to work at a lemon instead of a scintillating heat.

These special cases do not militate against the general fact that extremely low steel is usually red-short and weak.

The above is written for the consideration of those engineers who think they are going safe when they prescribe low tensile strength and excessive ductility. If these requirements meant the reception of pure, or nearly pure, iron, indicated by the low tenacity and high stretch, then they would be wise; but if they result, as they almost certainly do, in initially good material rotted by overdoses of oxygen the wisdom may not be so apparent.

NITROGEN.

The real influence of nitrogen is not known to the author. Percy shows that nitrogenized iron is hard, exceedingly friable, and causes a brilliant, brassy lustre. He also says nitrogen is driven out at a yellow heat; doubtless this is

true of the excess of nitrogen, but it has been shown in Chapter II that melting in a crucible will not drive the nitrogen out of Bessemer steel.

When crucible-steel not made from Bessemer scrap and Bessemer steel of equal analysis are compared in the tempered condition, there is almost invariably a yellowish tinge over the fresh Bessemer fracture which distinguishes it from the crucible-steel. The Bessemer steel is also the weaker. These differences are believed to be due to nitrogen.

Langley maintains his belief that oxygen is still the chief mischief-maker; the author believes nitrogen to be the more potent of the two; there is no known way to remove the nitrogen, and there the question stands.

ELEMENTS OF DISINTEGRATION.

It has been stated time and again that these impurities are elements of disintegration, and that it would be wise in every case to restrict the quantities allowable within reasonable limits, giving the steel-maker sufficient leeway to enable him to work efficiently and economically, and at the same time to keep the quantities of these impurities as low as possible.

On the other hand, able, successful, and conservative engineers have claimed that if the steel-maker meets their physical requirements as shown by prescribed tests they, the engineers, should be satisfied; that they should not interfere with chemical composition, as they had no fear of subsequent disintegrations.

This argument was answered by the statement that skilled steel-workers could manipulate poor steel so as to bring it up to the requirements; that the well-trained

workers in the bridge-shops would not abuse the steel; that the inherent deficiencies would not be developed; the work would go out apparently satisfactory; and that it might remain so for a long time, in the absence of unusual shocks or strains, but that in an emergency such material might fail because of deterioration where a purer material would have held on. In the absence of proofs such statements have been met with a smile of incredulity.

Fortunately some proofs are now at hand, and as the method of getting them has been obtained, more will follow from time to time.

In *Engineering*, Jan. 17, 1896, Mr. Thomas Andrews, F.R.S., M.Inst.C.E., gives the following cases:

A fracture of a rail into many pieces, causing a serious accident.

A broken propeller-shaft which nearly caused a disastrous accident.

Analysis of the rail:

Carbon	0.440
Silicon	0.040
Manganese	0.800
Sulphur	0.100
Phosphorus	0.064

It is clear that the sulphur is excessive, and that it was neutralized so as to make the steel workable by an excess of manganese.

Of the propeller-shaft Mr. Andrews says chemical analysis of outside and central portions of the shaft showed serious segregation.

"The percentage of combined carbon was nearly 50 per cent greater in the inside of the shaft than on the out-

side; the manganese was also in excess in the inside of the shaft; the phosphorus and sulphur had also segregated in the interior of the shaft to nearly three times the percentage of these elements found near the outside of the shaft."

Unfortunately Mr. Andrews does not give the analysis of the shaft.

A number of micro-sections of the rail and of the shaft were made and examined.

"Numerous micro-sulphur flaws were found, varying in size from 0.015 inch downward, interspersed or segregated in the intercrystalline junctions of the ultimate crystals of the steel, and being located in such a manner as to prevent metallic cohesion between the facets of the crystals, thus inducing lines of internal weakness liable to be acted upon by the stress and strain of actual wear."

The dimensions of these flaws in the rail varied from $.0150 \times .0012$ to $.0010 \times .0004$ parts of an inch.

In the shaft from $.0160 \times .0030$ to $.0020 \times .0016$ parts of an inch.

In the rail he found as many as 14 flaws in an area of only 0.00018 square inch, equal to nearly 60,000 flaws per square inch.

In the shaft he found as many as 34 flaws in an area of only 0.00018 square inch, equal to nearly 190,000 per square inch.

In speaking of the shaft he says: "In addition to blow-holes, air-cavities, etc., the interior of the shaft was literally honeycombed with micro-sulphide of iron flaws, which were meshed about and around the primary crystals of the metal in every direction." "The deleterious effects of an excess of manganese in interfering with the normal

crystallization of the normal carbide of iron areas were also perceptible."

As the number of micro-sulphur flaws in the shaft were about three times as many as in the rail, we may assume that the shaft contained at least as large a percentage of sulphur as the rail, and, owing to the general honeycombed structure, it would not be a far guess to assume that the steel was teemed wild.

"The deleterious effect of these treacherous sulphur areas and other microscopic flaws, with their prolonged ramifications spreading along the intercrystalline spaces of the ultimate crystals of the metal and destroying metallic cohesion, will be easily understood."

"Constant vibration gradually loosens the metallic adherence of the crystals, especially in areas where these micro flaws exist. Cankering by internal corrosion and disintegration is induced whenever the terminations of any of the sulphide areas or other flaws in any way become exposed at the surface of the metal, either to the action of sea-water, or atmospheric or other oxidizing influences. In many other ways, also, it will be seen how deleterious is their presence."

"Internal micro-flaws of various character are nevertheless almost invariably present in masses of steel, and constitute sources of initial weakness which not unfrequently produce those mysterious and sudden fractures of steel axles, rails, tires, and shafts productive of such calamitous results. A fracture once commencing at one of these micro-flaws (started probably by some sudden shock or vibration, or owing to the deterioration caused by fatigue in the metal) runs straight through a steel forging on the line of least

resistance, in a similar manner to the fracture of glass or ice."

It is understood that similar investigations are being carried out on an extensive scale by Prof. Arnold; in the meantime the above cases should satisfy any one that these impurities are elements of disintegration, and that the less there are of them in any steel the better for the steel.

It seems clear that if 10 sulphur will cause 60,000 flaws per square inch, 01 sulphur ought not to cause more than one tenth of that number; or, if an equal number, then they could only be one tenth of the size.

The segregation found in the shaft is so excessive that it would seen probable that there was a good deal of sin there also; but, even if it were unavoidable segregation, the harm would have been just so much the less if there had been less of total impurities present to segregate.

ARSENIC.

Arsenic is known to be very harmful in tool-steel, and it is proper to assume that it can do no good in structural steel. In any case where the properties of steel do not come up to the standard to be expected from the regular analysis examination should be made for arsenic, antimony, copper, etc. These are not as universal constitutents of steel as silicon, phosphorus, sulphur, and manganese, but they are present frequently, and in any appreciable amount they are bad.

XI.

THEORIES OF HARDENING.

The hardening of steel is such a marked phenomenon, and one of so great importance, that it has always attracted a great deal of attention, and many theories have been put forward in explanation.

Before chemistry was brought to bear upon the subject the proposed theories were based upon assumption, and as there were no proofs one had as much right to consideration as another, and none seemed to be altogether satisfactory.

Since science has taken up the question the theories are about as numerous as the investigators, and while no one can claim as yet to have settled the matter definitely, each one has an apparent basis of reason deduced from observed facts.

Among early observations it was noted that when unhardened steel and hardened steel were dissolved in acid a much larger amount of carbon was found in the solution of the unhardened than in that of the hardened steel. This led, first, to the distinction of combined carbon and graphitic carbon, a distinction that has been maintained through subsequent investigations. It seems to be well established now that there is a definite carbide of iron, Fe_3C, and some observers believe it to be the hard substance in hardened steel.

Following this came the announcement that these condi-

tions, *combined* and *graphitic* carbon, represented two different forms of carbon, and they were designated as *cement* carbon and *hardening* carbon; also as *non-hardening* and *hardening* carbon. Later investigation having established the existence of the carbide Fe_3C, this was claimed to be the hard body, but this has not met universal acceptance.

Another investigator, studying by means of the pyrometer and observing heat phenomena, concludes that hardening is due to an allotropic condition of the iron itself; that when iron is heated above the recalescent-point, and presumably below granulation, it becomes in itself excessively hard; that sudden cooling prevents its changing from this form, and so, when there is carbon present, the result of quenching is great hardness.

When steel is allowed to cool slowly to below recalescence, the iron assumes another form, and one which cannot be hardened by quenching; this latter is known as α iron, and the hardening kind as β iron. A later investigator finds it necessary to have a third allotropic form to meet some of the phenomena, which he designates by another Greek letter.

Another investigator establishes independently the saturation-point, which was pointed out and published twenty years ago, viz., somewhere about 90 to 100 carbon; he fixes the saturation-point at 89 carbon and gives the formula $Fe_{24}C$. He assumes that this is an exceedingly unstable carbide, that it is formed between recalescence and granulation, and can only be fixed by quenching, and that when steel is quenched the fixing of this carbide is the cause of hardness.

A still later investigation establishes this saturation-point

at about 100 carbon by observing that in hardened steel of 135 carbon there is a combination of 100 carbon which is the excessively hard part of the steel, and a portion containing the remaining 35 parts of carbon that is not quite so hard, and he suggests a fourth allotropic form to cover this part.

It is also suggested that steel should be considered and treated as an igneous rock; judging from the appearance of magnified micro-sections, this suggestion appears to be a happy one for the purpose of making comparisons.

The above theories of hardening, and others, are not to be regarded as antagonistic or contradictory, doubtless there are germs of truth in every one of them, or each one may be merely the individual's way of suggesting an explanation of the same observed phenomena, so that when a final conclusion is reached each may be found to have been travelling in the same direction by a different path. It is certain that able, patient, painstaking, men are working faithfully to produce a solution of the problem, and even if their ideas, as briefly given above, do seem to be contradictory it would only evince deeper ignorance and a stupid mind in any who should attempt to ridicule or unduly criticise honest work before it is completed. While these investigations are going on, and before any definite conclusion is reached, is there any well-established safe ground for the steel-worker and the engineer to stand upon? There certainly is a good working hypothesis for all to use, and one which it is believed will always be the right one to follow no matter what the final explanation of the remarkable phenomena of hardening, tempering, and annealing may prove to be.

After many years of careful experimenting and study

Prof. J. W. Langley came to the conclusion that no matter what the final result might be as to carbides, allotropic conditions, etc., that if steel were considered as iron containing carbon in solution, whether it were a chemical combination or a mere solution, and that cold steel be regarded as a congealed liquid in a state of tension, then all known phenomena could be accounted for, and all known conditions could be produced with certainty by well-known applications of heat and force.

When carbon is in the so-called combined condition, then the solution may be compared to pure sea-water; when the carbon is partly combined and partly graphitic, the solution may be compared to muddy sea-water, the mud representing the graphitic carbon.

When the carbon is practically all graphitic, as in over-annealed steel, then the solution may be compared to thoroughly muddy fresh water.

This hypothesis of solution agrees well with the saturation noted; then about 100 carbon is all that iron will dissolve without extraneous force; and higher carbon must be forced into solution by the work of hammers, presses, or rolls.

This gives reason to the experienced tool-maker's well-known preference for well-hammered steel.

The hypothesis of tension, probably molecular, covers all of the phenomena of excessive hardness due to high heat, which means high molecular motion checked violently by sudden quenching. It accounts for the progressive softening due to every added degree of heat, and it accounts for rupture, cracking, due to excessive heat or to any unevenness of heat.

Without this hypothesis of tension it is difficult to understand why quenching should rupture a piece of steel, no matter what the degree of heat, or how uneven it might be.

Without it, too, it is hard to see how successive additions of heat can cause gradual changes from β to α iron, or from an unstable carbide to an imperfect solution. It would seem that the allotropic changes, or the decompositions of carbides, must be more marked than the gradual changes from hard to soft which we know to take place by slow and gentle accretions of heat.

There is no property of steel known to the author which is not covered by Langley's hypothesis, and therefore it is put forward with confidence for engineers and steel-users to work by until the scientists shall have completed their investigations, and after that it is believed that it will be a safe working hypothesis, because science does not change facts, it only collates them and reveals the laws of action.

Under this hypothesis of Langley's we may define *hardness* as *tension, softness* as absence of tension.

This is not stated as established fact; it is given as a simple definition to cover the known phenomena until the final solution of the problem shall lead to a better explanation.

Regarding steel as a solution of carbon in iron, one important fact may be set down as established thoroughly: that is, that the more perfect the solution under all circumstances the better the steel.

Continued application of heat in any part of the plastic condition allows carbon to separate out of solution into a condition of mere mixture; it converts the clear sea-water into muddy water; this is the reason why so much emphasis has been given in previous chapters to the harmfulness of long-continued heating.

In every case, when steel is hot enough for the purpose desired, it should be removed at once from the fire.

XII.

INSPECTION.

CAREFUL and systematic inspection is of the utmost importance from the first operation of melting to the last act of the finisher.

Assuming that every operator is honest and conscientious in the performance of his work, the personal equation must be considered, as well as the exigencies of the many operations. The steel-maker must inspect his ingots to see that they are melted well and teemed properly, that they are sound and clean, and to determine their proper temper.

When work is finished, he must inspect it to see that it has been worked at proper, even heats, that it is correct in dimensions, and that all pipes and seams have been cut out. After all this has been done faithfully it were well that his work were done when it were well done. Such is not his happy lot; every successive manipulator may ruin the steel by carelessness or ignorance, and it is a gala day for a steelmaker when he does not receive some sample of stupid ignorance or gross carelessness, with an intimation that it would be well for him to learn how to make steel before he presumed to offend by sending out such worthless material. And sometimes, though not so often if he knows his business, he finds a complaint well founded; then he must regulate his own household and make his peace with his angry customer as best he can.

The engineer must inspect his steel to see that it is sound, and clean, and finished properly, as he has a right to expect that it should be.

It is not intended here to lay down rules for shop and field inspection,—that is an art in itself outside of the function or the experience of a steel-maker,—but some hints may be given as to the examination of steel as it comes from the mill, and it has been the aim in previous chapters to give such information as may enable an engineer to form a good judgment as to matters which are not likely to come to his knowledge in the course of ordinary practice.

Steel should be sound; it should be examined before it is oiled or painted. All pipe should be cut off; a pipe of any considerable size will show in the end of a sheared bar, and a careful observer will soon learn to detect it. If there is reason to suspect a pipe, file the place and the pipe will be revealed if it is there. Do not chip at it, for a chisel will often smooth a line which a file will bring out. In tool-steel there should not only be no pipe, there should be no star left in the bar. A "star" is a bright spot which shows the last of the pipe, not quite cut away; the steel is not solid in the star and it will not make a good cutting-edge; it may even cause a sledge to split.

SEAMS.

In tool-steel there should be no seams at all. Some makers declare that in high steel, seams are evidences of good quality; such a statement is the veriest fraud; it is hard to get any high steel free from seams, and therefore if the maker can get the user to believe that a seam is a good thing he can enhance his profit; that is, he can enhance it for a time until his fraud is understood.

Some seams are hard to see; when there is reason to suspect one, a little filing across the line will show it in a distinct black line if it is there. A file is an indispensable tool for an inspector, better than a chisel or a grindstone.

In machinery and structural steel a few small seams may be unobjectionable; too close inspection may lead to unnecessary cost without a compensating gain; still every engineer should reserve the right to determine what seams are allowable and what are not, for his own safety.

Laps should not be tolerated in any work.

Torn cracks on edges or surface indicate burned steel or red-short steel; they should not be allowed.

The grain of steel should be practically uniform, not too coarse, not with brilliant lustre, nor with a dark india-ink tint. With an even fine grain, a bright lustre may indicate a mild steel not worked badly. Inspectors must learn by practice what is tolerable and what is not, as it is impossible to lay down hard and fast rules; it is safe, however, to say that a fairly fine grain of even texture, not much lustre, and no india-ink shade, is indicative of good heating and proper working.

With these few general hints the subject must be left, for, like tempering, inspecting is an art in itself, and it cannot be taught in a book.

An expert inspector will see seams and pipes with his naked eye that a novice could not detect with an ordinary magnifying-glass.

It may do no harm to the inspector to suggest to him that amiability and good sense are the best ingredients to mix with sound judgment.

If he will cultivate these, and learn to distinguish between a mere blemish and a real defect, he will find his work made easy and pleasant; and he will be far less likely to have bad work thrust at him than he will if he makes it apparent that he regards himself as the only honest man.

XIII.

SPECIFICATIONS.

SPECIFICATIONS should cover three principal points:

Physical properties: Elastic limit; ultimate tensile strength; elongation; reduction of area.

Chemical constituents: Limiting silicon, phosphorus, sulphur, manganese, and copper; all other elements to be absent or mere traces in quantity, except carbon.

Finish and general condition: Fixing limit of variation in size from a given standard; conditions as to pipes, seams, laps, uniformity of grain, and other defects; no red-shortness.

PHYSICAL PROPERTIES.

It has been shown in Chap. V that tensile strength may be had from 46,800 lbs. per square inch to 248,700 lbs. per square inch.

There are published in many transactions and technical periodicals thousands of tests giving elastic and ultimate strength, ductility, etc., so that every engineer can find easily what has been done to guide him as to what he can get.

In almost every case the engineer must be the judge as to the requirements in each; therefore it would be useless to attempt to lay down any fixed rules or limits.

Many engineers adhere to low tenacity and high ductility

in the belief that they are securing that material which will be safest against sudden shocks and violent accidental strains.

Theoretically this appears to be correct, but if the statements made in the preceding chapters are credible it is plain that the limit to such safety can be passed, and that in insisting upon too low tenacity and high ductility the engineer may be getting simply a rotten, microscopically unsound material, through no fault of the manufacturer, who has been compelled to overmelt or overblow his steel to meet the requirements, and so reducing the quality of otherwise good material at no saving in cost to himself, and at a considerable cost in quality to the consumer.

Any manufacturer would rather check his melt between 10 and 15 carbon, or stop his blow so as to be sure not to overblow, if he were asked to do so, because it would save him time and expense, and it would yield sounder, better, and easier working steel.

It may not be wise yet for an engineer to fix limits as to blowing or melting, for the reason that neither he nor his assistants would know how to insure compliance, and in attempting to do it they might interfere too far with manufacturing operations and so involve themselves in responsibilities which they ought not to assume.

On the other hand, if they will let the carbon and tensile strength run up a little and reduce ductility slightly, it is safe to say that any manufacturer will be glad of the chance to help them to get the best results, which involve no extra cost.

Boiler-steel and rivet-steel usually suffer the most in this respect. A boiler should be tough, yet it is the belief of the author that boilers made of the 46,800-lb. steel of

which the analysis is given in Chap. V would not last half as long as boilers made of 65,000-lb. to 70,000-lb. steel when the increased strength was gained by added carbon and no overmelting was allowed.

In the same table the "Crucible-sheet" column gives a mean of 24 tests, and a mean analysis, of boiler-steel which has been in use in 12 boilers for nearly 16 years. The boilers are in perfectly good condition; they have been subjected to severe and very irregular usage, and they have been in every way satisfactory, Only one test-piece of the 24 was mild enough to stand the ordinary bending test after quenching.

That 46,800-lb. steel is remarkably pure chemically; it is unusually red-short. It would appear to some to be an ideal rivet-steel; it would stand a very high heat, it would head well and finish beautifully under a button-set. There is every probability that the majority of rivets driven of that steel would be cracked on the under side of the head, where the cracks would never be discovered until in service the heads flew off.

Rails are usually made of 40 to 45 carbon, tires from 65 up to 80 carbon, crank-pins as high as 70 carbon, with 85,000 lbs. to 95,000 lbs. tensile strength and 12% to 15% elongation.

It is difficult to see how a bridge or a boiler is to be subjected to any such violent usage as these receive daily; and while it is not advised that even 40 carbon should be used in boilers or bridges, although it would be perfectly safe, it does seem to be unreasonable to run to the other extreme to the injury of the material.

For steel for springs, and for all sorts of tools that are to

be tempered, there is no need of a specification of physical properties as they are indicated by testing-machines.

The requirement that they shall harden safely and do good work afterwards involves necessarily, high steel of suitable quality.

CHEMICAL CONSTITUENTS.

No engineer should, unless he be an expert steel-maker, attempt to specify an exact chemical formula and a corresponding physical requirement; in doing so he would probably make two requirements which could not be obtained in one piece of steel, and so subject himself to a back down or to ridicule, or both.

On the other hand, he may properly, and he should fix, a limit beyond which the hurtful elements would not be tolerated. Notwithstanding satisfactory machine tests, successful shop-work, and a liberal margin of safety, no steel can be relied upon that is overloaded with phosphorus, sulphur, manganese, oxygen, antimony, arsenic, or nitrogen.

In regard to silicon, it is common to have as much as 20 to 25 points in tire, with 55 to 80 carbon; such tires are made by the best manufacturers, and they endure well. But it is certain that good, sound steel can be made for any purpose with silicon not exceeding 10.

Structural steel can be made cheaply within the following limits:

Silicon....................	$< .10$
Phosphorus.................	$< .05$
Sulphur....................	$< .02$
Manganese..................	$< .50$ or even $< .30$
Copper...	$< .03$

Carbon to meet the physical requirements

Steel made within these limits and not overblown or overmelted must be better in every way than steel of

Silicon	$> .20$
Phosphorus	$> .08$
Sulphur	$> .05$
Manganese	$> .60$
Carbon to meet the same requirements	

A steel of the latter composition, or with no fixed limits, may be made cheaper than the first by a dollar or two a ton; but for any large lot it is believed that the first specification would be bid to at as low a price as if there were no specification; competition among manufacturers would fix that. At any rate there is no reason why an engineer should refuse to demand fairly pure material when he can do so at little or no extra cost.

Arsenic, antimony, or any other elements should be absent, or $< .005$.

FINISH AND GENERAL CONDITIONS.

As there can be no such thing as exact work done, there must be some tolerance as to variation in size. In standard sections, sheets, and plates this is usually covered by a percentage of weight; in forgings or any pieces that are to be machined the consumer should allow enough to insure a clean, sound surface. But it would be unwise to lay down any rule here, because conditions vary; a rolled round bar may finish nicely by a cut of from $\frac{1}{32}$ to $\frac{1}{16}$ of an inch, and so also a neatly dropped forging; an ordinary hammered forging might require a cut of $\frac{1}{4}$ or $\frac{3}{8}$ of an inch; such a forging might be made closer to size at a cost for extra time at the hammer far exceeding the saving of cost in the

lathe. These are cases where common-sense and good judgment must govern.

Pipes should not be tolerated if they can be discovered; because a pipe appears small in the end of a bar it is no evidence that it is not larger farther in.

Seams should not be allowed in any steel that is to be hardened; they should be a mininum in any steel. as they are of no possible use; small seams when not too numerous may do no harm in structural or machinery steel, and consumers should be reasonable in regard to them, or else they may have too high prices put upon their work, or too high heat used in efforts to close the last few harmless seams.

Burns, rough, ragged holes in the faces or on the corners, are inexcusable and should be rejected; the steel has been abused, or it is red-short: in either case the ragged breaks are good starting-points for final rupture.

Laps should not be permitted: they are evidences of carelessness; there can be no excuse for them.

Fins are sometimes unavoidable in a difficult shape; for instance, if a trapezoid is wanted, it may be rolled in this form:

or in this:

The consumer must decide which; if he wants sharp angles he must accept the fin and cut it off, or have it cut off by the manufacturer.

Rivet-steel should be tested rigidly for red-shortness, because red-short steel may crack under the head as the steel cools.

Emphasis is laid upon this because engineers will insist upon excessive ductility in rivet-steel, not realizing that they may be requiring the manufacturer to overdose his steel with oxygen to its serious injury.

No sharp re-entrant angles should be allowed under any circumstances where there is a possibility of vibrations running through the mass. All re-entrant angles should be filleted neatly.

No deep tool-marks should be allowed; a fine line scored around a piece by a lathe-tool, or a sharp line cut in a surface by a planing-tool will fix a line of fracture as neatly as a diamond-scratch will do it on a piece of glass.

Indentations by hammers or sledges should be avoided; they may not be as dangerous as lathe-cuts, but they can do no good, and therefore they are of no use.

XIV.

HUMBUGS.

STEEL is of such universal use and interest in all of the arts that it attracts the attention of would-be inventors perhaps more than any other one material.

Half-informed, or wholly uninformed, men get a smattering of knowledge of some one or more of the well-known properties of steel, make an experiment which produces a result that is new and startling to them, and at once imagine that they have made a discovery; this they proceed to patent and then offer it to the world with a great flourish of trumpets.

Many steel-workers, even men of skill, who know something of the difficulties that follow irregular work, or who are not quite fully informed as to the properties of steel, seize upon these discoveries in the hope that they have found a royal road to success where all old pitfalls are removed and their path is made easy.

Not wishing to discourage pioneers in legitimate efforts to improve, it is the object of this chapter to warn them against being too ready to spend their money because of flaming circulars or glib tongues. It is the duty and the interest of a steel maker to examine and test every apparently new suggestion, for the reason that there is still room for improvement, and he should let no opportunity for a betterment slip past him.

As a rule the steel-maker does test every claim that is laid before him, unless it be a repetition of some old plan

long since tried and found worthless. This is the bane of the steel-maker's life, and yet he must keep at this work so that he may know for himself whether anything of value has been discovered, and also that he may advise his clientage properly.

Inventions relating to the manufacture of steel have no interest for steel-users except as lively manufacturers may adopt the mistaken plan of flourishing trumpets to attract trade, not always giving a corresponding benefit to the consumer.

Examples of this sort of thing may be illustrated by so-called phosphorus steel, silicon steel, and aluminum steel; also the case mentioned before of parties recommending seams as evidences of excellence in high steel. Such efforts are sometimes costly to consumers until active competitive manufacturers expose the humbug.

Among the most absurd of such claims are those where a nostrum is used to convert ordinary Bessemer or open-hearth steel into the finest of tool-steel, equal to the best crucible-steel; for example, a patent to convert mild Bessemer steel into the finest tool-steel by merely carbonizing it by the old cementation process; this takes no account of the silicon, manganese, oxygen, and nitrogen in the mild Bessemer, makes no provision for their removal, and involves a costly method of putting carbon into poor stock in face of the fact that a Bessemer-steel maker can put the same amount of carbon there at practically no cost, and so produce a better material.

Among the humbugs that do not involve the manufacturer, the pet one is a nostrum for restoring burnt steel; these have been evolved by the dozen, in face of the fact that burned steel cannot be restored except by smelting,

and that overheated steel, coarse-grained steel, can be restored by merely heating it to the right temperature, a process which has been explained fully in Chapter VI.

Another pet is some greasy compound for toughening high steel so as to make it do more work. This is done by heating the steel to about recalescence and plunging it into the grease, perhaps once, or possibly two or three times; then working it into a tool and proceeding in the ordinary way. This will make a good tool; it is the partial annealing plan explained in a previous chapter. Now take a similar piece of steel, heat it the same way, lay it down in a warm, dry place alongside the forge-fire, and let it cool; then heat it and work it into a tool and it will beat the greased tool.

When all of these operations of restoring, partial annealing, annealing, etc., depend merely upon temperature and rate of cooling, why spend money for nostrums that add no possible benefit?

There is room for improvement in steel, great room for great improvements; they will come in time as science and knowledge advance, and great benefits to the consumers will come with them.

This chapter is not written to place difficulties in the way of legitimate improvement, but to warn unsuspecting people against quackery. Some of the humbugs are honest productions of well-meaning ignorance, and some that come from designing manufacturers are not entitled to such charitable designation. A knowledge of the simplest properties of steel will enable a thoughtful man to judge as to whether a proposed improvement is likely to be of any value or not, and the warnings given are intended as a protection to the unsuspecting and credulous.

XV.

CONCLUSIONS.

After perusal of the preceding chapters the reader may form a hasty conclusion that if steel be so sensitive as it is stated to be its use may be difficult and precarious, and that it must be handled in fear and trembling, lest the result should be a dangerous structure, and the builder must be in doubt as to its safety.

The conveyance of any such impressions is not intended at all; emphasis has been laid upon practices that are hurtful in order that every steel-user may know what to avoid, solely that he may then be sure that he has the best, the most reliable, and most useful material that is known to man.

WHAT TO AVOID.

He should avoid uneven heat, excessive heat, or too low heat. The range between orange red and the heat that will granulate is so great that no one who is not a bungler or indifferent need ever get outside of it.

The uniformity of temperature that is insisted upon is so easily seen that any person who is not color-blind should have no trouble in securing it by the simplest manipulations of the furnace.

Practical uniformity of the work put on a piece is readily secured by any mechanic of ordinary skill.

Red-short, cold-short, or honeycombed steel are easily detected, and, under reasonable specifications, the steel-makers can as easily avoid them.

Steel a little higher than most engineers favor in their specifications is certainly as safe as, and likely to be sounder than, extremely ductile steel.

Wild steel, resulting almost certainly in micro-honey-combs, if not worse, can only be avoided by the co-operation of the manufacturer, and engineers should impress this point with energy.

Such micro-unsoundness as is shown in Mr. Andrews's report upon a broken rail and propeller-shaft can be reduced to a minimum by insisting upon reasonably pure steel.

If sulphur, phosphorus, silicon, and oxygen are kept at a reasonable minimum, sulphides, phosphides, silicides or silicates, and oxides must be at a corresponding minimum.

That there is much room for improvement in the manufacture of steel is evident, and when means of getting rid of oxygen, nitrogen, and all other undesirable elements have been found the steel of the future will be very different in kindliness of working and in endurance of strains than that with which we are familiar.

It is believed, however, that no matter how perfect the manufacture may become, nor what the final theories of hardening, etc., may be, the properties stated in these pages will remain the same as long as steel continues to be essentially a union of iron and carbon.

Some other alloy or compound may displace carbon steel, and present an entirely new set of properties, but there is nothing of the kind in sight now, and engineers need have no fear of having a new art to learn very soon.

To one who has spent an ordinary business lifetime in

making steel, studying it, and working with it it becomes a subject of absorbing interest, if not of love; and steel when handled reasonably is so true that "true as steel" ceases to be a metaphor, it is then a fact which fills him with the most entire confidence.

Once more, steel highly charged with sulphur, phosphorus, arsenic, oxygen, and nitrogen is certainly highly charged with so many elements of disintegration; it takes more serious harm from ordinary deviations from good practice, such little irregularities as occur inevitably in daily working, than steel does which is more free from these elements.

Reasonably pure, sound, reliable steel can be had at moderate cost, and all consumers should insist upon having it.

Regular, uniform, reliable working can be had where it is required, and there should be no excuse for irregular grain, overheated work, uneven work, or any other bungling. Where skill is required and reasonable discipline is enforced, good work will not cost any more than bad work.

Many people still hold to the idea that there are many mysteries connected with steel, and that many unaccountable breaks occur which make it an unreliable material. It is hoped that what has been set down in these pages will go far to dissipate these supposed mysteries, and to give confidence to steel-users.

Many breaks are unaccounted for, but it is not within the author's experience that any fracture ever occurred that could not have been explained if it had been examined thoroughly in the light of what we know now. There is much to be learned, but there are no mysteries.

GLOSSARY.

THERE are many shop terms used in this book which may not be familiar to all steel-users.

They are in common use in steel-manufactories, and definitions of them will enable a steel-user to understand more clearly the common talk he will hear in the shops.

Blow-holes.—Blow-holes are the small cavities, usually spherical, which are formed in ingots as the steel congeals by bubbles of gas which cannot escape through the already frozen surface.

Burned.—Burned steel is steel that is reduced to oxide in part by excessive heating.

Check.—A check is a small rupture caused by water; it may run in any direction; it is usually not visible until steel is ruptured.

Chemical Numeration.—Chemical quantities are almost universally expressed in hundredths of one per cent, as explained in the body of the work. It is a very convenient numeration; any steel-worker, melter, hammerman, etc., will talk of 20, or 50, or 130 carbon; or 8 phosphorus; or 10, 15, or 25 silicon, etc.; and will talk intelligently, although he may not know the exact mathematical value of these points.

Dead-melting; synonym, killing.—Dead-melting—killing—means melting steel in the crucible or open hearth until it ceases to boil or evolve gases; it is then dead, it lies quiet in the furnace, and killed properly it will set in the moulds without rising or boiling.

Dry.—Steel is called *dry* when its fracture is sandy-looking, without lustre or sheen, and without a proper blue cast. There is more of a shade of yellowish sandstone. It is an evidence of impurity and weakness.

Fiery.—Fiery steel has a brilliant lustre; it is an evidence of high heat.

If the grain be fairly fine and of bluish cast, it is not necessarily bad in mild steel; in high steel or in tool-steel it should not be tolerated.

If the grain be large and of brassy cast, it is sure evidence of bad condition; the grain should be *restored* before the steel is used.

In hardened steel it is always bad, except in dies to be used under the impact of drop-hammers; in this case steel must be so hard as to be slightly fiery.

Grade.—Grade applies to quality, as crucible, Bessemer, or open-hearth grade. Or in the crucible, common, spring, machinery, tool, special tool, etc., etc. It does not indicate temper or relative hardness.

Honeycombed.—Unsound from many blow-holes. Usually applied to ingots. It is a bad condition.

Lap.—A lap is caused by careless hammering, or by badly proportioned grooves in rolls, or by careless rolling. A portion of the steel is folded over on itself, the walls are oxidized and cannot unite. A lap generally runs clear along a bar, practically parallel with its axis; it may be seen by a novice. Lapped steel should be rejected always.

Overblown.—Steel that has been blown in a Bessemer converter after the carbon is all burned; then there is nothing but steel to burn, and the result is bad.

Overheated.—Steel that has been heated too hot, and not quite burned; its fiery fracture exposes it. The grain of overheated steel may be restored, but restored steel is never as reliable as steel that has not been overheated. Overheating is a disintegrating operation.

Overmelted.—Steel that has been kept too long in fusion. The finest material may be ruined in a crucible by being kept in the furnace any considerable time after it has been killed. Open-hearth steel may be injured seriously in the same way. Prompt teeming after killing should be the rule.

Pipe.—A pipe is the cavity formed in an ingot when it cools; the walls chill first and nearly to the full size of the mould, then the shrinking mass separates in the middle, forming a pipe. A pipe should be at the top of the ingot; it may occur anywhere by bad teeming.

Point.—One hundredth of one per cent of any element. You have say 10 points of carbon, or 10 carbon; you want it raised a few points to 15 or 18 carbon.

Recalescence.—When a piece of steel is heated above medium orange color and cools slowly, at about medium orange—1100° to 1200° F.—the change of color ceases, then the color rises sometimes to bright orange, and afterwards the cooling goes on; this phenomenon is called recalescence. This is not yet a common shop term.

Restoring.—When a piece of overheated steel is re-heated to recalescence, kept there a few minutes, and then cooled slowly, its grain becomes fine and its fiery lustre disappears; this is called *restoring.* No nostrums are necessary.

Sappy.—Well-worked, good steel has a bluish cast, a fine grain, and a silky sheen. It is sappy; it is as good as it can be made.

Seam.—A seam is a longer or shorter defect, caused by a blow-hole which working has brought out to the surface and not eliminated. It usually, or always, runs in the direction of working. Seams are distinguished from laps by not being continuous; they are usually only an inch or two in length.

Short (Cold, Red, Hot).—*Cold-short* steel is weak and brittle when cold.

Red-short steel is brittle at dark orange or medium orange heat or at the common cherry-red heat. It may forge well at a lemon heat, and be reasonably tough when cold.

Hot-short steel is brittle and friable above a medium orange color; it may forge well from medium orange down to black heat.

Star.—A brilliant spot in mid-section showing that the pipe is not all cut away. It should be removed from tool-steel especially, as it may have considerable depth. It is of no use in any steel.

Temper.—Used by the steel-maker it means the quantity of carbon present. It is low temper, medium, or high; or number so and so by his shop numbers.

Used by the steel-user or the temperer it means the color to which hardened steel is drawn: straw, brown, pigeon-wing, blue, etc., etc.

Or, it is the steel-maker's measure of initial hardness; and it is the steel user's measure of final hardness.

Water-crack.—A crack caused in hardening; it may run in any direction governed by lines of stress in the mass. It is distinguished from a *check* by being larger, and usually plainly visible.

Wild Steel.—Steel in fusion that boils violently, and acts in the moulds like lively soda-water or beer does when poured into a glass.

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